Utilization of Waste Materials from Environmental Geotechnical Aspects(Dissertation_全文)

AUTHOR(S):

Katsumi, Takeshi

Utilization of Waste Materials from Environmental Geotechnical Aspects

September, 1996

Takeshi KATSUMI

Utilization of Waste Materials from Environmental Geotechnical Aspects

September, 1996

Takeshi KATSUMI

Summary

The subject of this thesis is the utilization of waste materials through a geotechnical stabilization method from the standpoint of environmental geotechnology. The present state of waste generation is such that a vast amount of materials are being consumed by the construction industry, while waste disposal sites are quite limited. It is vital, therefore, that more types of waste materials be recycled in order to properly utilize resources and preserve the environment. A closed system of material flow should be established so that the concept of "sustainable development" can be achieved. To promote geotechnical waste utilization, the possibility of creating a positive environment by geotechnical waste utilization is proposed through experimental and analytical studies. Negative influences on the environment by the reuse of waste materials for geotechnical engineering and possibilities for controlling them are also studied.

In the first stage of this research, a stabilization method for geotechnical waste utilization is evaluated with ash, slag and sludge wastes. Strength-developing characteristics, durability, hardening mechanisms and leachate characteristics are tested on fluidized bed combustion coal fly ash, stainless-steel slag, and municipal solid waste incinerated fly ash. Experimental studies clarify that the coal fly ash and the stainless-slag can be used as geotechnical materials for embankments, subgrade, and other similar applications. As for the stabilization of municipal solid waste incinerated fly ash, the multiple use of cement and coal fly ash as a stabilizer can bring about strength development, high soaking durability, and the containment of heavy metals. The method can therefore be effective for environmental landfilling.

The stabilization and utilization of waste sludge discharged from construction sites are also discussed. The effects of hardening agents on sludge stabilization are clarified, and the hardening mechanisms of sludge stabilization are discussed from the viewpoint of the formation of hydrated products. A system which utilizes waste slurry and involves dehydration or solidification is proposed. It was found that the density (ρ) and the funnel viscosity (μ) of waste slurry can be used effectively as indexes for judging whether a slurry would best be treated by dehydration or by solidification for recycling purposes.

In the second stage of this research, the possibility for negative and positive environmental influences is discussed.

A new technical method, the "Bagged WRP Method," makes use of waste rock powder (WRP) and is proposed from the standpoint of waste utilization and environmental mitigation. Bagged and hardened mixtures are both light in weight and high in strength, and no remarkable changes in the environmental quality of the cured water are observed. A stability analysis clarifies that bagged WRP is more advantageous to the construction of sunken levees than rock or concrete blocks because of its light weight. It not only has an effect on sunken levees applications, but extends the applicability of levee construction itself and accompanies man-

made tidal flat construction for environmental mitigation or creation.

The environmental impact caused by the geotechnical recycling of surplus soil, stabilized by cement, is discussed. The characteristics of alkali migration from stabilized soil are evaluated and the importance of the soil's alkaline neutralization ability for a filtration layer is emphasized. The design concept for alkaline migration control is proposed for its application to embankments. One must not only consider the neutralization ability of the filtration soil, but also the permeability of the materials and the geometric dimensions of the earthen structures. In conclusion, efforts made to prevent seepage water from passing through the stabilized layer will curb the negative impact on the environment due to geotechnical waste utilization.

Acknowledgments

The research reported herein originated when the author was a master's degree student of the School of Civil Engineering, Kyoto University. The author wishes to acknowledge the supervision, guidance, support, assistance, and encouragement of many people.

The author would like to express his sincere gratitude to Professor Masashi Kamon, Supervisor, Disaster Prevention Research Institute (DPRI), Kyoto University, for suggesting the theme, for his insightful guidance, and for his continuous encouragement throughout the course of this research. Professor Kamon has provided a splendid environment in which the author was able to conduct the research, and many chances were given to the author to attend not only national symposia but also international conferences held abroad. Professor Kamon spent many hours helping the author to understand the geotechnical waste management as well as the importance of the research field of "Environmental Geotechnology."

The author is also indebted to Professor Yutaka Terashima, Department of Environmental and Sanitary Engineering, Kyoto University and Professor Yuzo Ohnishi, Department of Civil Engineering Systems, Kyoto University for their critical reading the manuscript and fruitful suggestions.

The author would like to extend his thanks to Professor Koichi Akai, Professor Emeritus of Kyoto University, for his direction and encouragement. Grateful acknowledgments are also extended to Professor Toru Shibata, Professor Emeritus of Kyoto University and Dr. Hideo Sekiguchi, Associate Professor, Department of Civil Engineering, Kyoto University, for useful discussions and for giving the author access to the experimental facilities in the Soil Mechanics Division, Department of Civil Engineering, Kyoto University.

The author is also grateful to Dr. Mamoru Mimura, Associate Professor, DPRI, Kyoto University, for his practical discussions, academic and non-academic advice, and continuous encouragement.

Dr. Supakij Nontananandh, Associate Professor at Kasetsart University, Bangkok, spent many hours teaching the author how to perform laboratory tests while he was a doctoral student of the School of Civil Engineering, Kyoto University. His contribution is greatly appreciated.

Thanks are also extended to Mr. Hiroki Shimizu, Technical Officer, DPRI, Kyoto University, for his cooperation in the experimental works.

Significant contributions made by the students in Professor Kamon's laboratory are gratefully acknowledged. The students include Mr. Hidekimi Imanishi (Maeda Construction Co. Ltd.), Mr. Yoichi Sano (Nippon Steel Co., Ltd.), Mr. Sho Oyama (Konoike Co., Ltd.), Mr. Masahiko Ota (East Japan Railway Company) and Mr. Akira Nakashima (Nikki Co., Ltd.).

The author would also like to thank Mr. E. Yamauchi of Obayashi Corporation, Mr. T. Murayama of Moricho-gumi Co. Ltd., Mr. M. Matsushima of Matsushima-saiseki Co. Ltd., Mr.

T. Nagayasu of Morishita Chemical Industry Co. Ltd. and Mr. Y. Wakimura of Mitsuboshi Chemical Ltd. Partnership for their help in carrying out the field experiments.

Thanks are also due to the members of the various committees that the author joined, namely, the Research Committee on Treatment and Potential Use of Industrial Wastes (Japanese Geotechnical Society), the Committee on Materials Science and Technology for Soil Stabilization (Society of Materials Science, Japan), the Editorial Committee of an 'Introduction to Environmental Geotechnology' (JGS), and the Organizing Committee of the Second International Congress on Environmental Geotechnics (JGS).

Lastly, the author would like to thank his family- his late father, Taiji, his mother, Masako, his sister, Mariko, and his wife, Junko, for their great support and encouragement.

CHAPTER 1

Introduction

1.1 General Remarks

Rapid industrialization and urbanization in recent decades have caused serious environmental problems. In particular, environmental pollution due to the generation and management of waste materials has become one of the most emergent problems to which the human being should find a solution. A wide spectrum of materials, regarded as waste, are being discharged in large quantities throughout the world. The disposal and dumping of such waste causes the geo-environmental contamination of both soil and groundwater and results in the lack of space for waste disposal.

In order to mitigate these environmental problems related to waste management, much research has been performed to help prevent the generation of waste, to reduce the volume of waste being disposed of, to recycle and reuse waste materials, and to turn hazardous waste into non-hazardous waste by an intermediate treatment process. Geotechnical engineering is expected to play a particularly important role in the above goals, and thus, a new field called "environmental geotechnology" has been born.

In recent decades, the recycling and reuse of various wastes as geo-materials have been aggressively researched in Japan using ground improvement and soil stabilization techniques in the field of environmental geotechnology. This type of research is very important due to national conditions. In other words, the population in Japan is high and industrial activities are basically concentrated in certain areas to a large degree. Only a limited amount of space on a narrow piece of land and a small amount of natural resources are available. Consequently, various types of waste materials have been generated in large quantities, and many of them are not being utilized but merely disposed of at the limited disposal sites which will be exhausted in the near future. It is estimated that the disposal areas which are now being employed will be completely filled with municipal waste in 8 years and industrial waste in 1.5 years, respectively. Therefore, to reuse the wastes as construction materials, such as geo-materials, can be an effective alternative scheme in terms of saving natural resources and reducing the volume of waste to be disposed of.

From the 1960s to the 1970s, the geotechnical practice of waste utilization was limited to materials possessing positive properties for use as construction materials, such as coal ash and iron slag, which have hardening characteristics. Considering the present state of waste generation in Japan, a large amount of materials are consumed by the construction industry, while disposal sites for dumping waste are quite limited and the contamination of numerous sites existing due to hazardous waste dumping has been detected. From the viewpoint of resource utilization and environmental preservation, therefore, it is vital that many more types of waste materials be recycled. A closed system of material flow should be established in order to realize the concept of "sustainable development."

Positive and negative impacts on the environment caused by geotechnical waste utilization should be satisfactorily investigated and discussed as the waste may be filled in/on the ground in large quantities as a result of the promotion of geotechnical waste utilization. If geotechnical waste utilization can not only prevent a negative environmental impact but also have a positive effect on the environment and its preservation, that will become our actual strategy. Therefore, "value added" is an important concept for the promotion of waste utilization. Incidentally, environmental influences due to the geotechnical reuse of waste materials should be taken into account. A concept and some methods for evaluating and controlling influences on the environment are required for establishing the geotechnical reuse of waste.

In this study, the utilization of waste materials through the geotechnical stabilization method is evaluated in terms of environmental geotechnology. To promote geotechnical waste utilization, the possibility of creating a positive environment by geotechnical waste utilization is proposed through experimental and analytical studies. Negative environmental effects and their control through waste reuse for geotechnical engineering are also studied.

1.2 Literature Review

1.2.1 Waste Generation and Governmental Regulations

The generation and management of waste materials are strongly affected by the technical and the non-technical conditions of the country, namely, natural resource production, available land area, population, politics, economy, and the consensus of the citizens. In the United States of America, research efforts to establish a design method for a waste containment system and the remedial technology of contaminated sites have been positively performed in the field of geotechnical engineering since the 1970s. This is because geo-environmental contamination due to leakage from a waste landfill and the dumping of toxic chemicals, such as a contaminated site in the state of New York called the Love Canal, was widely publicized and caused an uproar in 1978. An important process then stemmed from promulgation by the US Congress in 1980 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA),

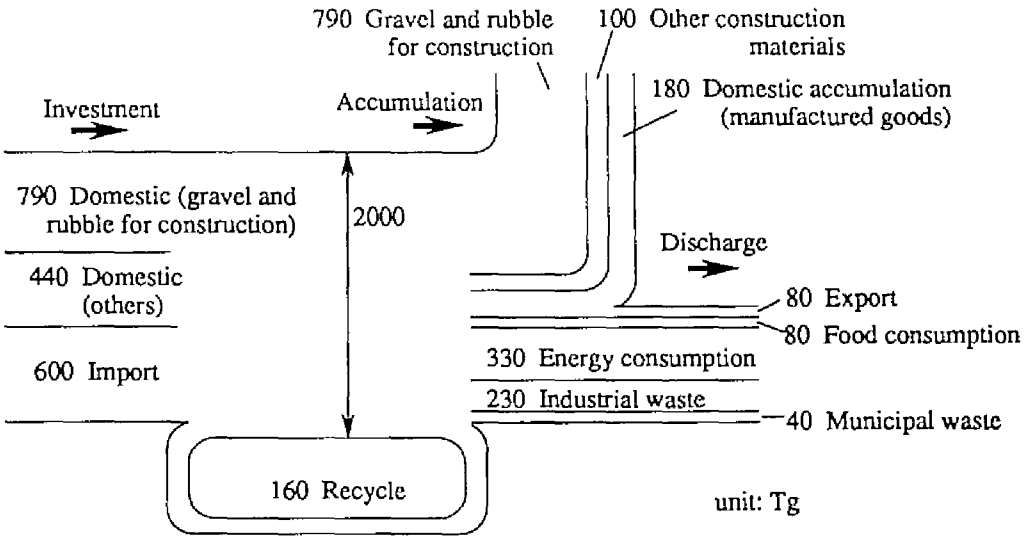


Fig. 1.1. Material Balance in Japan (1987).

which became commonly referred to as "Superfund." Many geotechnical engineers are actively engaged in investigating, designing, and actually working on landfill construction and remediation of contaminated sites. In European countries where the land area is limited and the population is relatively high, volume reduction and the utilization of waste or by-products have been a concern as well as waste containment landfill designs and contaminant remediation. Conditions in Japan are probably similar to those in Europe. The material balance in Japan for 1987 is shown in Fig. 1.1 which exhibits the large amount of natural resources, both domestic and foreign being invested and the limited amount of waste recycling. However, the possibility of merely disposing this waste will be unfeasible in the near future because of the limited land space. To reduce the waste volume, research and development on incineration treatment and recycling methods are being conducted.

According to their origin, waste materials can be roughly classified into industrial, municipal, mining, and nuclear wastes. Their generation and state of management can differ according to the conditions of each country. Therefore, the management of industrial and municipal wastes is a field of world-wide importance.

In Japan, waste management has been prescribed by the Waste Disposal and Public Cleansing Law (WDPCL) which was established in 1967 and then revised in 1992. The law stated that waste materials can be classified into industrial and municipal wastes, as shown in Fig. 1.2. The generation of these wastes is enormous; industrial and municipal wastes are discharged at an annual rate of 350,000 Gg and 50,000 Gg, respectively, about half of which are reused for various purposes related to technological developments.

Legislation on waste management and environmental regulations has been revised in recent years, as the importance of environmental issues has been strongly publicized around the globe.

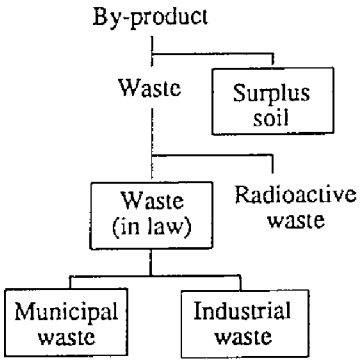


Fig. 1.2. Classification of wastes and by-products in Japanese legislation.

The Public Nuisance Countermeasures Basic Law (PNCBL) was the basis for environmental regulations. However, it was only prescribed for environmental protection from public nuisance. The PNCBL was replaced by the Environmental Basic Law (EBL) in 1994. The EBL aims at establishing social responsibility that would both reduce the burden on the environment and promote the concept of sustainable development. The Waste Disposal and Public Cleansing Law (WDPCL) was fundamentally revised in 1992 in order to procure a better public health by means of a reduction in waste generation and proper waste treatment. However, certain problems still remain with waste utilization. For example, once a material is regarded as waste, it must continue to be referred to as waste, even if it has been improved for recycling.

The Law for the Promotion of Utilization of Recyclable Resources (LPURR) was established in 1991. It aims at the sound development of the state of the economy by means of securing the effective use of limited resources and promoting the use of reclaimed resources. This law specifies Designated By-Products (shown in Table 1.1), Specified Industries (paper industry, glassware manufacturing, construction), and Designated Manufactured Goods (automobiles, air-conditioners, TV-sets, refrigerators, washing machines, cans) because these by-products, or goods from these industries, should be reused in order to save limited resources.

Table 1.1 Designated by-product in LPURR

Type of By-product	Industry
Slag	Iron and Steel Industry
Coal Ash	Electric Power Generation Work
Surplus Soil Waste Concrete Waste Asphalt-Concrete Waste Wood	Construction Work

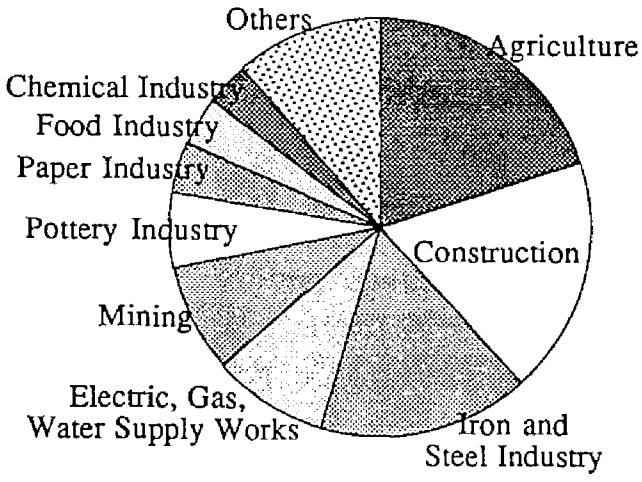


Fig. 1.3. Waste generation ratio from industries.
(Fiscal Year 1985, Total Generation: 312.3 Tg)

Table 1.2 Present state of by-product generation (1993)

Type of by-product	Generation	Recycle (%)	Reduction (%)	Disposal (%)
Surplus soil	43.7×10^{8} m^3	47	-	53
Waste sludge	1.5×10^{7} t	2	6	92
Waste concrete	2.6×10^{7} t	67	-	33
Asphalt-concrete mixture	2.2×10^{7} t	78	-	22
Mixed by-product	0.7×10^{7} t	6	9	85
Waste wood	0.8×10^{7} t	26	14	60
Total waste	7.6×10^{7} t	48	3	49

The construction industry strongly affects waste generation and management. Not only are large amounts of materials being discharged by the construction industry, namely, waste concrete mass, waste asphalt mass, waste sludge, and excavated surplus soil, but also natural resources are being used up for construction purposes in large quantities, as shown in Fig. 1.1. Figure 1.3 indicates that the waste discharged from construction works adds up to about 20 % of the total generation of industrial waste. Surplus soil is not included because by law it is not regarded as waste. The by-products generated by the construction industry are listed in Table 1.2. The generation of surplus soil is estimated at 44,000,000 m^3 per year. Surplus soil should be reused because it exists in the natural ground. Surplus soil is legally regarded as a Designated By-Product, and a Technical Manual for the Utilization of Surplus Soil was established in 1994 in order to promote the recycling of such by-products. Other construction wastes or by-products should also be reused to reduce the volume being disposed of. In particular, an effort to utilize waste sludge is strongly needed as its recycling ratio is still low.

1.2.2 Fundamentals of Environmental Geotechnology and Geotechnical Waste Utilization

The early roots of environmental geotechnology can be traced to the Specialty Session on "Geotechnical Engineering and Environmental Control" held at the 9th International Conference on Soil Mechanics and Foundation Engineering (ICSMFE) in 1979. From the 1950s to the 1970s, environmental problems related to geotechnical engineering were publicized. They were limited, however, to problems related to public nuisance caused by uncontrolled industrial activities, such as ground subsidence due to groundwater drawing, air and water pollution, or noise and vibrations caused by uncontrolled construction works. The discussion at the above-mentioned session focused on (1) the role of geotechnical engineering in the protection of the environmental quality, and (2) the geotechnical aspects of environmental protection (Moh 1978). At the 10th ICSMFE held in 1981, Sembenelli and Ueshita (1981) emphasized the importance of establishing the field of environmental geotechnology, succeeding the fruits of the session of the 9th ICSMFE. The purpose of environmental geotechnology is not only to cope with the negative environmental impact which is already in existence, but also to predict future problems and deal with them positively so as to contribute to environmental control.

In recent years, many research projects in the field of environmental geotechnology have been performed and conferences have been held. Kamon (1992) explained that the three main groups of research themes in the area of environmental geotechnology are the creation of a better environment, the prevention of environmental risks to human activities, and the prevention of danger to human life caused by natural hazards. Problems which relate to waste materials, namely, the reusing of reclaimed land with waste and/or the utilization and recycling of waste, are among the very most important subjects. Topics associated with cleaning up a ground which has been contaminated by toxic waste and safe designs for landfill and geotechnical waste utilization have been the major themes at conferences held in recent years, such as those organized by Fang (1986), Usmen and Acar (1992), JSSMFE (1994), Carrier III (1994), and Acar and Daniel (1995). Important information on waste management technology has been summarized from the standpoint of environmental geotechnology by Daniel (1993) and Rowe et al. (1995).

The utilization of waste materials for geotechnical engineering is one of the major subjects in environmental geotechnology. While waste materials should be classified by the processes of the generating industries, they need to be understood based on their career and related characteristics. For example, waste materials are divided into three groups for the treatment process, namely, waste generated from incineration or melting (coal ash, iron slag, and incinerated ash), inorganic waste generated by crush (waste concrete powder and waste rock powder), and organic or inorganic waste generated as-is without any treatment (waste sludge, waste oil, waste plastics, and waste tires). Residue is always generated by incineration or melting which results from thermal power generation, iron and steel refining, or the incineration

Table 1.3 Present grade of utilization of various wastes.

Type of wastes		Cement material				Road material			Soil material					Brick	Liner	Other waste treatment	Merits	Demerits
		Raw material	Blended cement	Soil stabilizer	Aggregate	Asphalt pavement	Base course	Subgrade	Filling-up	Embank-ment	Recla-mation	Caisson filler	Back-fill					
Coal ash	Pulverized coal fly ash	1	1	2	2	1	2	2	1	2	1	1	2	2		2	A2,A3,B1	
	Pulverized coal clinker ash			2	2		1	2	2	2		3	3	2			A1,A2	
	Fluidized bed combustion coal ash			2			2	2	3	2		3	3		3	2	A2,B1	U
Slag	Blast furnace slag	2	1	2	1		1	2	2	2				2			B1,B2	H
	Converter furnace slag	2		2		1	2	2	2	2							B1	E,H
	Electric furnace slag			2			2		3	3							B1	E,H
Sewage sludge	Sewage sludge incineration ash (by lime flocculants)	2		2		2	1	3	1	1	3			2			B1	H
	Sewage sludge incineration ash (by polymer flocculants)				2		1		1	3	3			1			B2	H
	Dehydrated sludge	2			2		4	4		3	3			3			B2	H,G
Waste sludge	Pulp sludge incineration ash					2	2	2		3	3	3	3	2		2	A2,B1	D
	Others	3		2										3			B1,B2	H
	Waste rock powder	1		2	2		3	3	1	3	3			4				
	Waste concrete powder			2			2	2	3	3	3			4				
	Waste soil	4	4	4	4	4	2	1	1	2	2							
	Waste slurry	4	4	4	4	4		2	2	2	2				3		A3	S
	Municipal waste incineration ash				4		3							3				H,D
	Cement kiln dust	1		2			2									2	B1	
	Waste oil	4	4	4	4	3	3			3	3	4	4	4	4		B3	G
	Waste plastic	4	4	4	4	2			4	4	4	4	4	4			B3	C
	Waste expanded polystyrol	4	4		4				2	2		3	2	4			B1	C

1) Grade of utilization - 1: utilized, 2: confirmed for utilization, 3: can be considered for utilization, and 4: can not be considered for utilization.
2) Merit for utilization - A1: permeability, A2: light weight, A3: flow ability, B1: hydration characteristics, B2: baking characteristics, and B3: containing oil.
3) Demerit for treatment utilization - H: containing heavy metals, D: containing dioxin, U: containing unburned carbon, C: chemical durability, G: production of gas or smell, S: soft condition, and E: expansion characteristics.

treatment of waste sludge and municipal waste. The characteristics of these wastes depend on their raw materials, the incineration temperature and time, and the type of boiler system. They are classified roughly into fly ash, bottom ash, and slag. The second group of wastes are generated in large quantities from construction works. The wastes categorized in the first and second groups are thought to be stabilized by compaction or chemical hardening, and then utilized as road or embankment materials according to their stabilization effect. The last group of wastes contains waste sludge, waste oil, waste plastics, and so on. The treatment of these wastes is very difficult for various technical and economical reasons.

Many cases of waste utilization have been researched and developed, and are summarized in Table 1.3. The geotechnical uses include reclamation, embankments, subgrade, base course, and other similar applications. When contemplating waste utilization, it is important to grasp the waste characteristics and the generating conditions. The waste characteristics include whether the waste materials are inorganic or organic and whether they contain toxic substances or not. Generating conditions mean when, where, and what amount of waste materials are being generated. As shown in Table 1.3, some kinds of wastes, such as pulverized coal fly ash and blast furnace slag, have already been applied to construction works, including geotechnical engineering. However, many types of waste materials can not be practically reused in construction works and research efforts on the utilization of them are therefore encouraged.

Environmental influences due to waste utilization in construction engineering are an important concern. Research on the environmental impact caused by waste utilization has been limited. In addition, the possibility for creating a better environment based on waste usage has not yet been satisfactorily addressed. New concepts and methods to evaluate and control the possibility of negative and positive environmental influences are needed.

1.3 Objectives and Contents of the Thesis

The objectives of this study are to demonstrate the possibility of stabilizing and utilizing certain types of waste materials and to evaluate the positive and negative influences of geotechnical waste utilization on the environment.

In terms of waste management, in particular waste disposal, it is strongly required to reduce the volume of waste, and the addition of other materials to waste is not recommended. From the standpoint of waste utilization, however, the addition of stabilizers or other chemicals has an effect on efficient and reliable treatment. Therefore, the chemical stabilization by using the additives is considered essential. In this study, some types of materials, namely, cement, Carbonated-Aluminate Salt (CAS), and even certain types of waste materials, are used in order to stabilize the waste materials. The CAS, a newly developed material, is a cement-based mixture containing $Ca(OH)_2$, $Al_2(SO_4)_3$, and Na_2CO_3, and there are different kinds of CAS

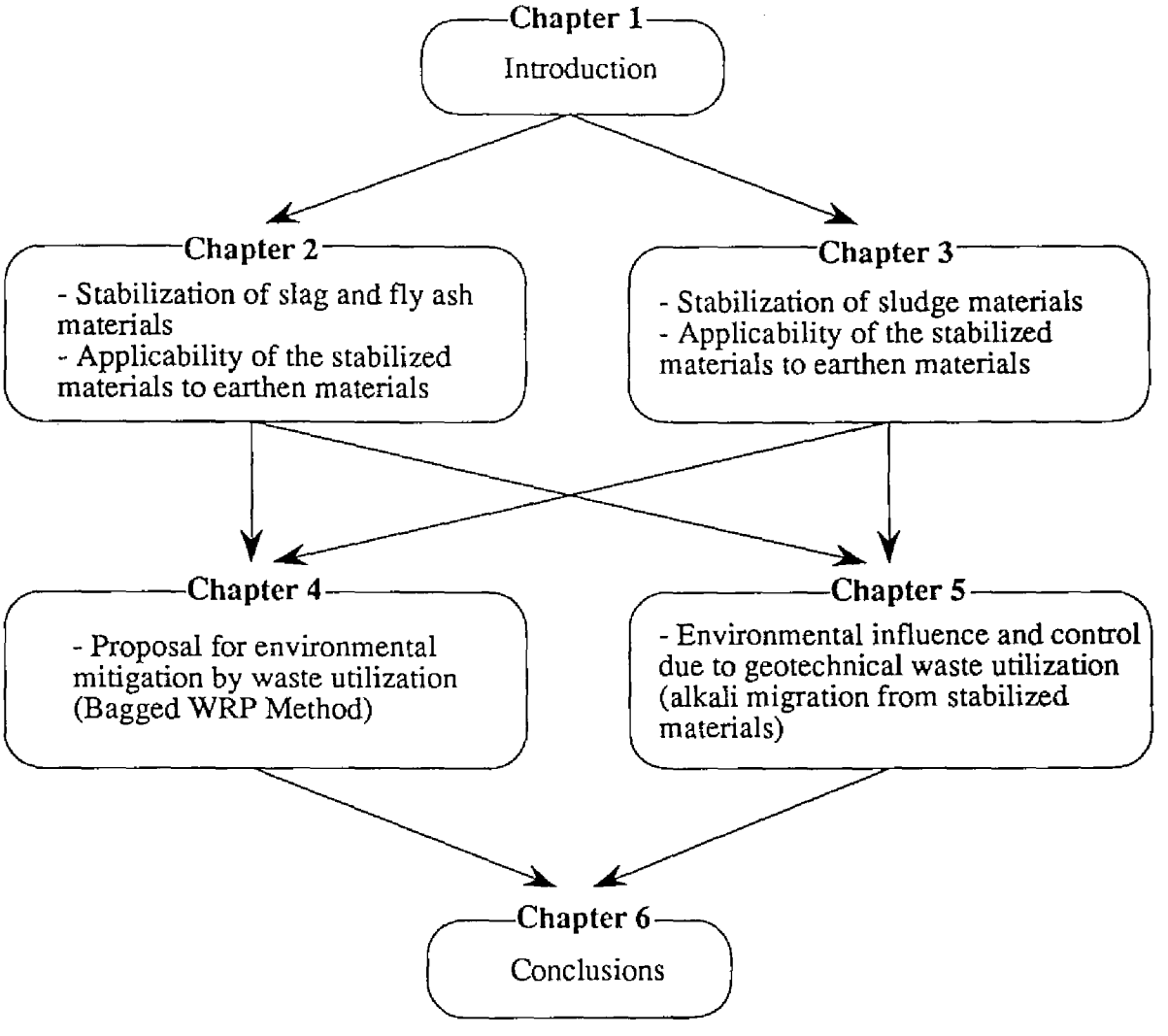


Fig. 1.4 Contents and flow of this study

based on the mixing ratio. It has been shown that CAS is effective as a hardening material for soft clays or waste materials (Kamon et al. 1989; Tomohisa 1989; Nontananandh 1990).

The thesis is divided into 6 chapters. The constitution of the thesis is shown in Fig. 1.4. Materials used and approach applied in this study are listed in Table 1.4. In the experimental study, the unconfined compressive strength is mainly used for the index to evaluate the effect of stabilization, while durability characteristics, hardening mechanisms, and environmental impacts are also discussed.

In this chapter, the objectives and the contents of the thesis are clarified and general background information on this research is presented.

Chapter 2 discusses the effectiveness of the stabilization and utilization of ash and slag materials, namely, fluidized bed combustion coal fly ash (FCA), stainless-steel slag (S-Slag), and municipal solid waste incinerated fly ash (MSW fly ash). These materials are created by

Table 1.4 Materials used and approach applied in this study

Chapter	Materials	Approach
2	- Fluidized bed combustion coal fly ash - Stainless-steel slag - Municipal solid waste incinerated fly ash	- Laboratory experimental study Hardening characteristics Durability characteristics Environmental impact - Field experimental study Workability
3	- Dredged sludge - Waste sludge	- Experimental study Hardening characteristics Dehydration characteristics Applicability of waste materials
4	- Waste rock powder	- Laboratory experimental study Hardening characteristics Environmental impact - Field experimental study Workability Environmental impact - Analytical study Field applicability
5	- Surplus soil	- Experimental study Alkali neutralization ability Alkali migration - Analytical study Design concept

industrial activities and discharged. It has recently become necessary to stabilize and recycle them properly. The application of such wastes for geotechnical purposes, based on the ground improvement technique, is proposed through assessing strength development, durability, and leaching characteristics.

In Chapter 3, the treatment of sludge which is discharged from construction works is discussed for utilization purposes. After a brief summary of the present state of regulatory requirements and treatment methods, the cement stabilization method is evaluated through an assessment of the strength development mechanism, the durability, and the environmental impact. The author also proposes a treatment system for slurry from construction sites which consists of two methods, namely, dehydration and solidification. This system is expected to bring about efficient treatment, a decrease in volume, stabilization, and recycling.

Discussions in Chapters 4 and 5 are based on the knowledge obtained in Chapters 2 and 3.

In Chapter 4, a new technical method referred to as the "Bagged WRP Method" is proposed. The method utilizes a by-product, waste rock powder (WRP) and promotes waste utilization as well as environmental mitigation. In this method, woven or non-woven fabric bags are filled with a dry mixture of WRP and hardening agents and are solidified by soaking. This procedure will not only further geotechnical waste utilization, but will also improve the quality of the environment due to the construction of man-made tidal flats behind sunken levees.

Chapter 5 deals with the environmental impact caused by the geotechnical recycling of surplus soil stabilized by cement. The mechanisms of alkaline leachate from stabilized soil and the neutralization ability of the soil for a cover or a filtration layer is discussed, and a design concept for alkaline migration control is proposed. The minimum thickness of a filtration layer for a stabilized-soil embankment is estimated through experiments and a parametric analysis.

In Chapter 6, conclusions and future scope are presented.

References for Chapter 1

Acar, Y.B. & D.E. Daniel (eds.) (1995). *Geoenvironment 2000,* Geotechnical Special Publication No.46, ASCE, 1822p.

Carrier III, D. (ed.) (1994). *Proc. 1st International Congress on Environmental Geotechnics*, BiTech, 1014p.

Daniel, D.E. (ed.) (1993). *Geotechnical Practice for Waste Disposal,* Chapman & Hall, 683p.

Fang, H.Y. (ed.) (1986). *Proc. International Symposium on Environmental Geotechnology,* 685p.

JSSMFE (1994). *Proc. First National Symposium on Environmental Geotechnology*, 272p.

Kamon, M. (1992). "Definition of environmental geotechnology," *Proc. 12th ICSMFE,* Vol.5, pp.3126-3130.

Kamon, M., K. Sawa and S. Tomohisa (1989). "On stabilization of hedoro by using cement group hardening materials," *Jour. Society of Materials Science, Japan*, Vol.38, No. 432, pp. 1092-1097 (in Japanese).

Moh, Z-C (1978). "Geotechnical engineering and environmental control," *Proc. 9th ICSMFE,* Vol. 3, pp.559-561.

Nontananandh, S. (1990). "Industrial waste utilization as construction materials by chemical stabilization," Dr. Eng. dissertation, Kyoto University, 347p.

Rowe, R.K., R.M. Quigley & J.R. Booker (1995). *Clay barrier systems for waste disposal facilities,* E & FN SPON, 390p.

Sembenelli, P. & K. Ueshita (1982). "Environmental geotechnics -State of the art report-," *Proc. 10th ICSMFE,* Vol. 4, pp.335-394.

Tomohisa, S. (1989). "Stabilization of problem soils and industrial wastes by cement or lime hardening and estimate method of strength development," Dr. Eng. dissertation, Kyoto University, 284p (in Japanese).

Usmen, M.A. & Y.B. Acar (eds.) (1992). *Environmental Geotechnology*, Balkema, 594p.

CHAPTER 2

Stabilization and Utilization of Fly Ash and Slag Materials

2.1 General Remarks

Thermal treatment is one of the most effective processes that has been discovered by man for various purposes. In some cases, the incineration method is used to generate energy and a power supply, such as by thermal power generation. The melting process is also important in that it makes raw natural resources useful, for example, iron and steel refining. In order to sanitate and reduce the useless or unwanted materials that are discharged throughout daily and industrial activities, the incineration technique can also be applied. Incineration plays an important role in waste management, and there are many incineration plants for the intermediate treatment of waste materials in Japan.

The generation of residue, therefore, is not negligible due to the treatment methods of incineration or melting which result in thermal power generation, iron and steel refining works, or the incineration treatment of industrial and municipal wastes. The characteristics of these types of waste materials depend on their original materials (raw coal, raw iron ore, or wastes) as well as the incineration parameters (incineration temperature, amount of air injected into the furnace, degree of turbulence, and time period). The kinds of residue generated are roughly classified into (1) fly ash collected from fuel gas, (2) bottom ash left at the bottom of boilers, and (3) slag produced by melting. Their generation comprises a major part of all waste generation. The stabilization and utilization of these waste materials are necessary from an environmental point of view.

Much research has been conducted on the possible application of these types of waste residue as construction materials because of the positive properties of the materials. In particular, the reuse of pozzolanic waste, generated by incineration or melting, as a geo-material or concrete material has been suggested. Typical materials in this group are coal ash and steel slag, etc. (e.g. Gidley et al. 1984; Mehta, 1989; Kamon et al. 1991). Representative examples of this application are cement concrete which contains coal fly ash or burst furnace slag and the soil

stabilization method using mixtures of lime and fly ash. Considering the present state of waste generation in Japan, a large amount of materials are consumed by the construction industry, while disposal sites for the waste this industry produces are quite limited, and the contamination of numerous sites due to hazardous waste dumping has been detected. Therefore, the development of recycling and stabilizing methods for many more kinds of waste materials is needed from the standpoint of resource utilization and environmental preservation as well as for the purpose of noticing the positive properties of materials. A closed system for resources and material flow should be established for the sake of sustainable development.

Solidification is considered to be an effective option for waste stabilization and utilization (Kamon et al. 1991; Means et al. 1995). Some kinds of waste can be solidified with cement or lime, while others can be hardened only by compaction without hardening agents, such as pulverized coal fly ash and blast furnace slag. However, there are some types of steel slag and MSW (municipal solid waste) incineration fly ash which are difficult to solidify by conventional methods of cement stabilization because of their expansive or soluble characteristics (Kuwayama et al. 1992; Kamon et al. 1994). In addition to the development of a stabilization method, the environmental impact caused by waste utilization by solidification, such as groundwater contamination after construction or dust distribution during construction should be addressed.

In this chapter, the effectiveness of stabilizing and utilizing three waste materials, namely, fluidized bed combustion coal fly ash (FCA), stainless-steel slag (S-slag) and municipal solid waste incinerated fly ash (MSW fly ash), will be discussed. In recent years, stabilizing and recycling these waste materials have become imperative. The following section 2.2 summarizes the present states on the generation and management of these materials. The utilization of FCA, based on ground improvement techniques, will be discussed in Section 2.3, and an investigation of the basic properties of FCA, an evaluation of the Non-Dusty Method for the promotion of FCA utilization, and an application to soft ground improvement are included. Section 2.4 will illustrate the effective utilization of S-slag when stabilized with one kind of cement-based stabilizer (Carbonated-Aluminate Salt; CAS). Its subsequent application as a road material will then be discussed through experimental works on strength and durability. The solidification and stabilization of MSW fly ash will be described in Section 2.5, in which the stabilization method using cement and FCA is proposed in terms of strength development, durability and the prevention of heavy metal leachate.

2.2 Generation and Management of the Presented Materials

2.2.1 Coal Fly Ash from Fluidized Bed Combustion Systems

Fluidized bed combustion coal fly ash (FCA) is a by-product of the thermal power generation

Table 2.1 Combustion system of thermal electric power generator in Japan

Industry and boiler capacity	Stoker combustion system	Pulverized combustion system	Fluidized combustion system	Total
Electric industry				
below 500 t/h	0	7	1	8
500-1000 t/h	0	22	0	22
1000-2000 t/h	0	10	0	10
above 2000 t/h	0	4	0	8
total	0	43	1	44
Other industry				
below 50 t/h	15	0	6	21
50-100 t/h	7	14	9	30
above 100 t/h	2	41	4	47
total	24	55	19	98

industry. The conservation of our energy supply is one of the most important priorities because of the lack of natural resources in Japan. The use of thermal electric power generators to stabilize the energy supply has increased in recent years. In particular, the use of thermal power generators which employ the fluidized bed combustion system is spreading widely as an independent means of electrical power generation in chemical industries and in iron and steel manufacturing plants due to the many advantages this system provides, as shown in Table 2.1 (Hosoda 1994). Such advantages include the efficiency of operating on the small scale necessary for independent power generation, causing less air pollution than conventional methods, such as the pulverized coal combustion system, and its ability to accept various qualities of raw coal for combustion. Recently, some electric supply companies have also been planing to construct fluidized bed combustion systems for thermal power generation facilities. Consequently, FCA generated as a by-product by fluidized bed combustion boilers, the production of which is currently only about 600 Gg per year in Japan, will increase markedly. The present situation which entails most of the FCA being disposed of rather than being utilized leaves much room for improvement.

The use of pulverized coal fly ash has been proposed and realized for civil engineering purposes, such as for concrete, soil stabilization, backfilling, and the making of bricks (e.g., Toth et al. 1988; Mehta 1989; Janardhanam et al. 1992; Joshi et al. 1992; Kawasaki et al. 1992; Horiuchi et al. 1995). Despite these advances in the utilization of pulverized coal ash, most FCA produced at present is not being used but is simply being disposed of. One reason for this disposal is that the characteristics of FCA differ from those of the coal ash ordinarily utilized, such as pulverized coal fly ash. Due to the combustion by which it is produced, FCA contains large amounts of unburned carbon, lime, and gypsum. The latter two components, however, are thought to contribute to the hardening reaction in solidification. Therefore, it has been proposed that a greater amount of FCA be applied as road subgrade or subbase material (Ohora

et al. 1990; Shinano 1991; Nishi et al. 1994; Behr-Andres and Hutzler 1994; Hosoda 1994; Rogbeck and Elander 1994; Pandey et al. 1995). For recycling purposes, the utilization of FCA to stabilize large quantities of waste slurry/sludge and surplus soils, generated from foundation or excavation works, has been reported (Kamon and Katsumi, 1994). As the fly ash can adsorb and contain harmful chemicals, such as heavy metals and organic or acid compounds, its application to liner materials for waste disposal facilities has been evaluated (Edil et al. 1992; Fujiwara et al. 1992; Wright III and Shackelford 1995). The engineering properties required for application should be clarified further, and an effective strategy is needed to realize and promote FCA utilization.

2.2.2 Stainless-Steel Slag (S-Slag)

Stainless-steel slag (S-slag) is the electric furnace slag discharged from the steel making process. The generation of all types of slag from the metallurgical industry has reached some 40,000 Gg per year, more than 85% of which is reused as road material, cement material, fertilizer, pottery material, and soil stabilizers. Slag can be classified as blast furnace slag, converter furnace slag or electric furnace slag. Blast furnace slag and converter furnace slag are produced through a process in which iron ore is made into iron, and electric furnace slag is generated from the steel making process which uses scrap iron as the main raw material. While the production of blast furnace slag and converter furnace slag has decreased in recent years, the generation of electric furnace slag is on the rise. The characteristics of electric furnace slag vary according to the method of production; for example, some types of steel are made in electric furnaces, e.g., carbon steel, stainless steel, nickel steel, etc. The trouble with this material is that electric furnace slag is efflorescent and has expansion characteristics like the converter furnace slag (Kuwayama et al. 1988). Most of this slag production (2500 Gg per year), therefore, is merely disposed of in reclamation areas.

While there is widespread use of blast furnace slag for cement and concrete materials, the reuse of converter slag and electric furnace slag for the construction industry has not become popular. A manual for the utilization of these types of slag has been produced by the Steel Slag Association, Japan (1985), although research on electric furnace slag has been very limited. Kuwayama et al. (1990 and 1992) clarified the basic properties of slag for utilization purposes. Electric furnace slag is classified into two categories, namely, oxidizing slag and reducing slag, depending on the production process. Oxidizing slag is produced in the process to eliminate porosity and the impervious composition of molten steel by oxidizing, while reducing slag is produced in the process to eliminate the oxygen in molten steel and to adjust the steel composition. It was clarified that oxidizing slag has similar expansion characteristics to those of converter slag. It is believed these two kinds of slag expand by an increase in volume associated with the hydration of free lime. Slag with the expansion characteristics eliminated by aging can be utilized as construction material (Kuwayama et al. 1992). Reducing slag forms products by hydration, such as calcium silicate hydrate ($CaO \cdot SiO_2 \cdot H_2O$; CSH) and hydrated gehlenite ($CaO \cdot$

$Al_2O_3 \cdot SiO_2 \cdot H_2O$; CASH), in the long run. Thus, it not only exhibits hydraulic properties, but also continues to increase in volume (Kuwayama et al. 1992). The contribution of S-slag to the strength development of dredged sludge was clarified, however, and the potential utilization of S-slag as an additive to soil stabilizers was presented (Kamon and Nontananandh 1990). Unfortunately, reducing slag is still mostly disposed of because its properties, such as hardening and expansion, have not yet been quantified.

2.2.3 Municipal Solid Waste Incinerated Fly Ash (MSW Fly Ash)

Municipal solid wastes (MSW) are usually incinerated by the intermediate treatment facilities of local governments in Japan. Consequently, about 6000 Gg of bottom ash and fly ash are discharged from incinerators annually and most of them are disposed of in landfill sites. Since incineration can cause harmful elements and toxic substances to be concentrated and compounded, respectively, most of them remain in the MSW fly ash and the fly ash must be carefully treated prior to its disposal to prevent environmental pollution. In the present system of incinerators in Japan, the MSW fly ash is mixed with the bottom ash, which is less harmful. Then it is collected from incinerators and is disposed of. Under the Waste Disposal and Public Cleaning Law revised in 1992, however, newly constructed incinerators are required to be facilities where fly ash can be collected separately from bottom ash, and prior to the disposal, the fly ash must be treated by a method of melting, cement hardening, the addition of a chemical agent, or extraction. In terms of the containment of harmful chemicals and volume reduction, the melting method is considered to be the most effective option available. However, the method cannot achieve resource recovery in spite of its demand for high cost and energy (Hiraoka and Sakai 1994; Kokado 1994). Solidification by cement hardening has been thought of as another recommended method (Shimaoka and Hanashima 1994). In the case of solidification, the government requires that the cement mixing ratio be more than 150 kg/m^3 and the compressive strength be higher than 10 kgf/cm^2 (= 980 kPa).

Research has been carried out on the geotechnical utilization of MSW bottom ash (e.g., Maher et al. 1992; Hartlen 1994). Research on the utilization of MSW fly ash as a construction material has been conducted recently in the US and Europe (Triano and Frantz 1992; Hudales 1994; Gerdes and Wittmann 1994). Research on the stabilization of MSW fly ash from a geotechnical viewpoint was also conducted by Tay and Goh (1989) and Poran and Ahtchi-Ali (1989). Poran and Ahtchi-Ali (1989) reported that the MSW fly ash in the US contains just a small amount of NaCl and can be stabilized effectively by lime and applied as a road material. In Japan, however, MSW fly ash usually contains a large amount of salt which affects the hardening reaction of cement or lime (Kamon et al. 1994). Thus, a more effective method for MSW fly ash solidification is needed from technical, environmental and economical point of view.

2.3 Utilization of Fluidized Bed Combustion Coal Fly Ash (FCA) Based on the Ground Improvement Technique

2.3.1 Basic Properties of FCA

Table 2.2 shows a comparison of the chemical compositions of FCA and pulverized coal fly ash (PCA). The FCA was collected by a precipitator in the fluidized bed combustion system, with a boiler temperature in the range of 800-1000℃ to minimize the contents of SOx and NOx in the flue gas. Consequently, a large amount of unburned carbon remained in the FCA, and the particles had a variety of non-spherical shapes and rough surfaces, as shown in Photo 2.1, while the particles of the PCA were spherical in shape due to the high temperature of the boiler. These characteristics make the use of FCA as a flowable replacement material in concrete or backfilling like PCA very difficult. However, since the particle shape is considered to lead to an increased adsorption of chemical substances, including harmful components, the utilization of FCA as a liner material at waste disposal sites has been proposed (Fujiwara et al. 1992). A further important feature of FCA is that it contains lime and gypsum as a result of the use of desulphurizers in the combustion boiler as a preventive measure against air pollution. This leads to the possibility of utilizing FCA, by hardening stabilization, as a geo-material in large quantities.

The FCA used in this experimental study originated from a fluidized bed combustion boiler

Table 2.2 Comparison of chemical composition of coal fly ash (Unit: %)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Ig-loss
PCA	50-55	25-30	4-7	4-7	0-1	1-2	0-1	0-1	1-2
FCA	25-40	15-25	1-3	10-30	1-2	0-1	0-1	3-8	10-30

Note: PCA and FCA stand for pulverized coal fly ash and fluidized combustion coal fly ash, respectively.

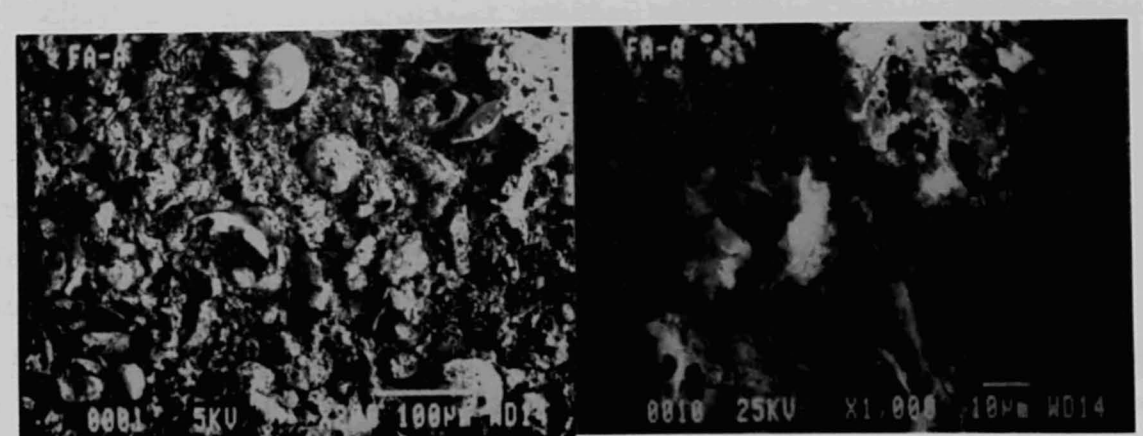


Photo 2.1 SEM micrographs of FCA (FCA I)

Table 2.3 Physical properties and chemical composition of FCAs used

(a) physical properties

	Particle density (g/cm^3)	Optimum water content (%)	Maximum dry density (g/cm^3)	Grain size distribution (%) - 75 mm	75 - 5 mm	5 mm -
FCA I	2.28	82.5	0.70	3.3	83.9	12.8
FCA II	2.40	72.0	0.75	10.0	81.9	8.1

(b) chemical composition (unit: %)

	SiO_2	Al_2O_3	T-F	CaO	MgO	K_2O	Na_2O	SO_3	Ig-loss
FCA I	23.8	16.5	2.9	10.8	1.6	0.3	0.2	1.8	39.2
FCA II	25.8	16.2	1.7	8.5	0.5	0.6	0.4	4.2	33.7

(c) Leachate component (unit: mg/l)

	T-Hg	Cd	Pb	Org-P	Cr(VI)	As	CN^-
FCA I	< 0.0005	< 0.01	0.02	< 0.01	0.04	< 0.001	< 0.01
FCA II	< 0.0005	< 0.01	< 0.01	< 0.01	0.1	0.02	0.1
Criteria [1)]	< 0.005	< 0.3	< 0.3	< 1	< 1.5	< 0.3	< 1

Note 1) : The criteria of harmful components established for landfilling by Environmental Agency, Japan.

used as an independent electrical power plant in an iron foundry. Table 2.3 shows the physical properties and the chemical compositions of the FCA used. The FCA consisted of particles equivalent in size to silt grains, the same as those in PCA. The ignition loss depended upon the unburned carbon content, which exceeded 30% for the samples used. The FCA contained a relatively low content of CaO and gypsum in comparison to the ordinarily generated FCA (shown in Table 2.2). As the FCA used here consisted of fine grain particles with low density, it generated much dust during handling.

It is important to assess the environmental impact induced by the utilization of waste materials such as FCA. A leachate test established by the Environmental Agency in Japan was carried out, wherein the material was smashed to pieces less than 5 mm in diameter, soaked in a ratio of 50 g of waste per 500 ml of distilled water (pH 5.8-6.3), and stirred for 6 hours. Then, the test liquid was separated by filtering. The leachate levels of harmful components from the FCA were very low against the criteria for landfilling, and therefore, it can be utilized effectively without concern for its environmental impact.

2.3.2 Strength Characteristics of FCA with Hardening

Figure 2.1 shows the relationship between the strength and the mixing conditions of FCA. The specimens were mixed and prepared in accordance with the Practice for Making and Curing Compacted Stabilized Soil Specimens Using Rammer (Standard of the Japan Cement Association, CAJS L-01-1990, which is equivalent to ASTM D1632 standard using Compression Test Specimen Molds). Mixing the FCA with water resulted in a change in the consistency of the samples. This indicates that the FCA samples, by absorbing mixed water and exhibiting a dry surface early in the mixing, changed to a moist spherical clod because of the prolongation of the mixing time which is an indicator of the dissolution of the reactive

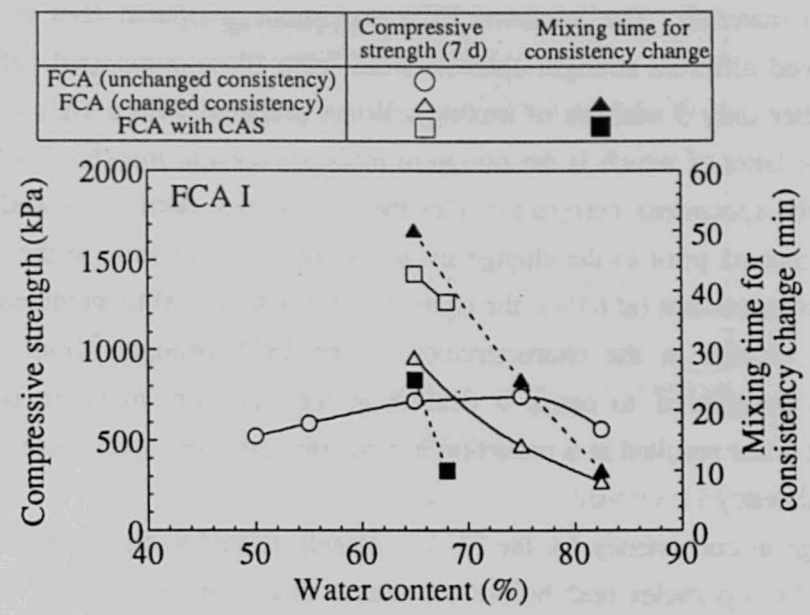
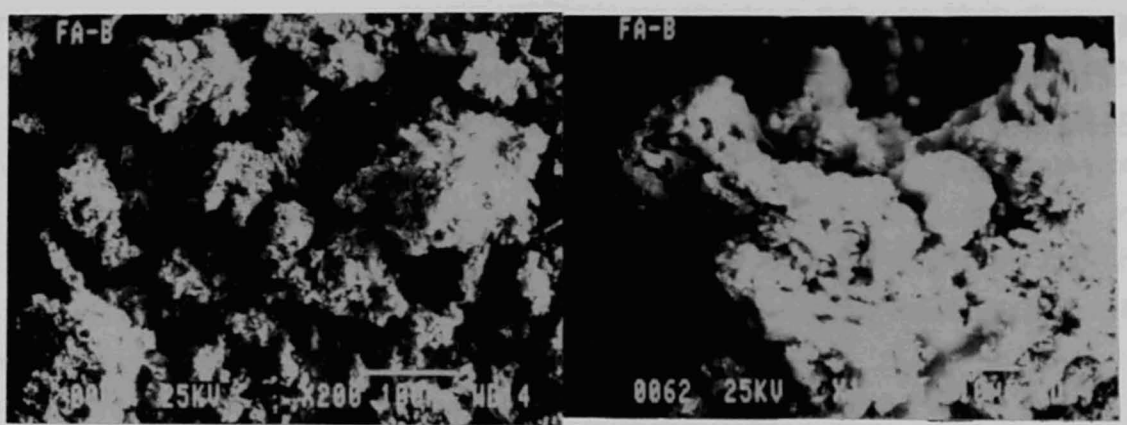
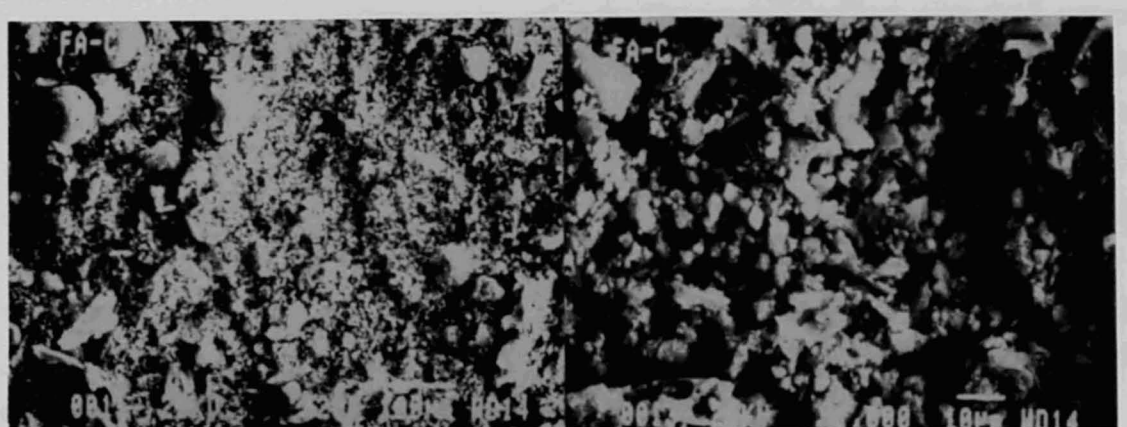


Fig. 2.1 Strength development of hardened FCA



(a) before consistency change



(b) after consistency change

Photo 2.2 SEM micrographs of FCA I mixed with water

composition in materials. The hardened FCA specimens, prepared after the consistency had changed, showed different strength characteristics from those compacted before the change in consistency (after only 5 minutes of mixing). When prepared with a high water content (75% and 82.5%, the latter of which is the optimum moisture content measured before the change in consistency), the specimens compacted after the consistency change showed a lower strength than those compacted prior to the change in consistency. Conversely, in the case of specimens with a lower water content (at 65%), the change in consistency led to an increase in compressive strength. This change in the characteristics of the FCA brought about by the change in consistency is considered to cause a decline in the optimum moisture content. Excessive saturation with water resulted in a reduction in strength compared with those specimens with no change in consistency.

The change in consistency for the FCA is closely related to the hardening reaction. Photo 2.2 shows the FCA particles both before and after a change in consistency. The samples which had undergone a change in consistency showed a modification from a rough shape to small spheres, in comparison with the non-spherical particles shown in Photo 2.1. The X-ray diffraction intensity of C_3S (alite; one kind of compound in cement), shown in Fig. 2.2, illustrates the acceleration of dissolution by the change in consistency, which results in more CSH (calcium silicate hydrate; $CaO \cdot SiO_2 \cdot H_2O$) products than in specimens with no change in consistency.

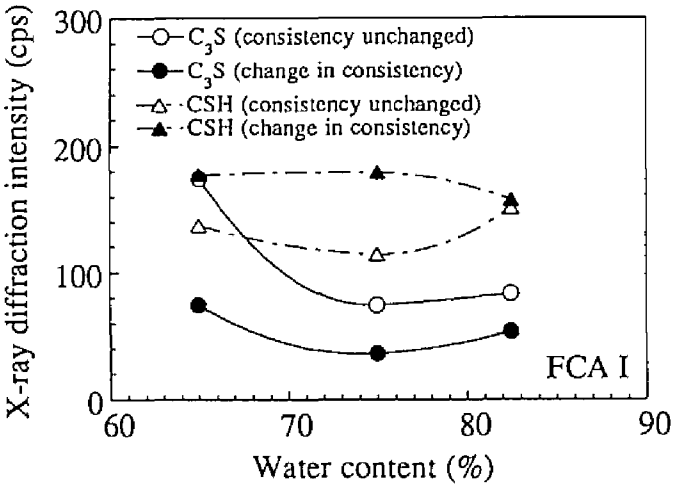


Fig. 2.2 X-ray diffraction intensity of hardened FCA

Table 2.4 Leachate properties of FCA

Mix proportions of samples (wt, %)			Leachate ions (mg/l)		
FCA I	Water	Na_2CO_3	Si	Al	Ca
50	100	15	85	180	45
50	100	-	54	0	117

Note: Sample solutions were prepared by filtering the mixtures.

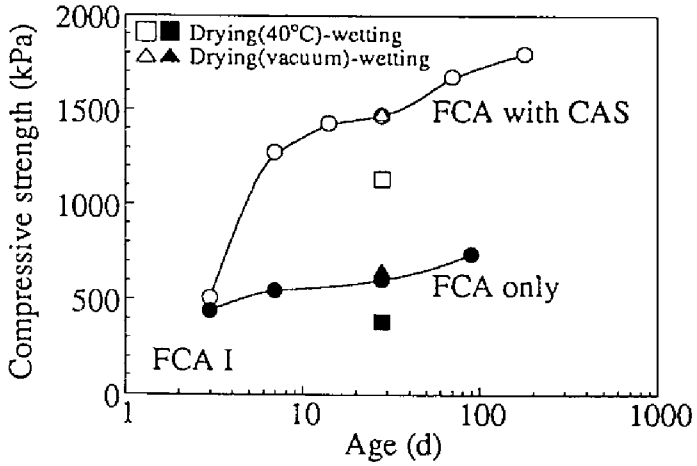


Fig. 2.3 Strength characteristics of hardened FCA

While the change in consistency for specimens with a water content of 65 % is thought to be what allows for their reuse as base-course materials, according to their strength development (1 MPa, set for use in Japan), mixing for even longer periods (50 minutes) was not reasonable for field applications. The addition of CAS (Carbonated-Aluminate Salt; one kind of cement-based stabilizer), which shortened the mixing time for a change in consistency and increased the strength, as shown in Fig. 2.1, suggested the possibility for a practical utilization of FCA as a geo-material. The effectiveness of CAS will be addressed in Section 2.4.1 (2). The composition of the CAS presented here was 85%, 5%, 6%, and 4% for cement, $Ca(OH)_2$, $Al_2(SO_4)_3$, and Na_2CO_3, respectively. Na_2CO_3, a component of CAS, promotes the dissolution of Si^{4+} and Al^{3+}, as shown in Table 2.4, and is considered to accelerate the change in consistency and the hardening reaction.

Figure 2.3 shows two strength-time curves for hardened FCA, both of which changed in consistency with CAS (w_0 = 68%) and without CAS (w_0 = 82.5%). Both mixtures showed that a long curing period leads to an increase in strength. The samples treated with CAS retained compressive strengths above 1 MPa after drying-wetting and can be thought of as suitable subbase materials. This drying-wetting test method was conducted in accordance with the method proposed by Kamon et al. (1993), and will be described in detail in Section 2.4.2 in which 6 cycles of drying (in a 40℃ oven or a 20℃ vacuum desiccator) and wetting (by soaking) were performed after 7 days of curing. Even the specimens with no change in consistency retained a strength of 300 kPa, making possible their reuse as materials for embankment building and subgrade, as by law the suggested strength after 7 days of curing should sustain 100-200 kPa of stress for these purposes.

2.3.3 Characteristics of FCA Treated by the Non-Dusty Method

The use of FCA leads to a dusty construction environment, due to the low density fine grain particles. Table 2.5 shows the dust characteristics of FCA and some other materials. The dust

Table 2.5 Dust level of FCA and other materials

Sample	FCA II	Ordinary Portland cement	Non-dusty stabilizer
Dust level (mg/m^3)	56.4	12.8	7.5

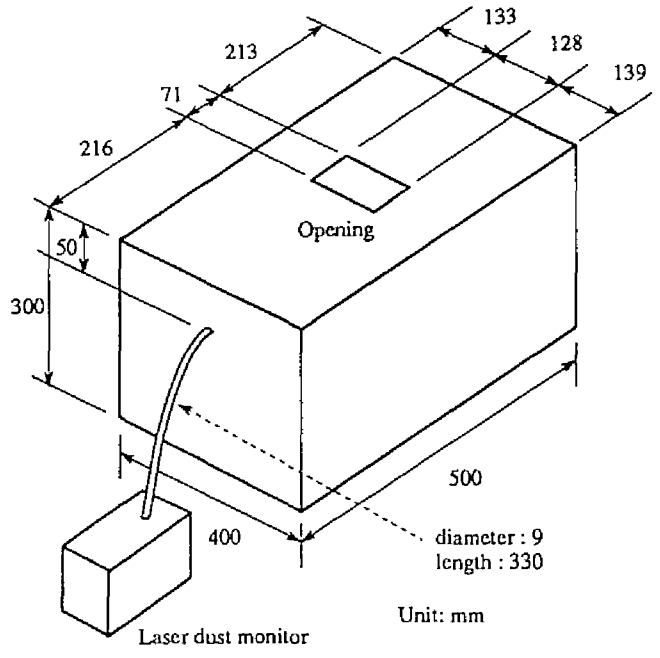


Fig. 2.4 Equipment for dust measurement

level was measured as follows; 100 g of the sample were dropped into a box 40 x 50 cm in width and 30 cm in height through an upper opening (7.1 x 12.8 cm), and the dust levels at a height of 25 cm (in the box) were measured with a laser dust monitor, as shown in Fig. 2.4. The FCA raised much more dust than ordinary Portland cement, thus, a non-dusty treatment method is required for the widespread application of FCA as a geo-material.

In this study, the applicability of the "Non-Dusty Method" using oil, as proposed by Sawa et al. (1993), was evaluated. This method has been developed and established for cement-based stabilizers. Oil contributes to the prevention of dust raising, but not to the acceleration of the hardening reaction, differing in this respect from the addition of water. Figure 2.5 shows the dusting characteristics of FCA mixed with several kinds of oil. The addition of oil resulted in the settling of FCA dust as effectively as the addition of water, because it changed the dry FCA powder to a wet powder condition. When the FCA treated by the Non-Dusty Method was compacted with the optimum water content, the reduction in strength induced by the addition of oil was negligible, as shown in Figure 2.6. The FCA treated by this method shows characteristics which suggest its applicability for use in road or embankment construction.

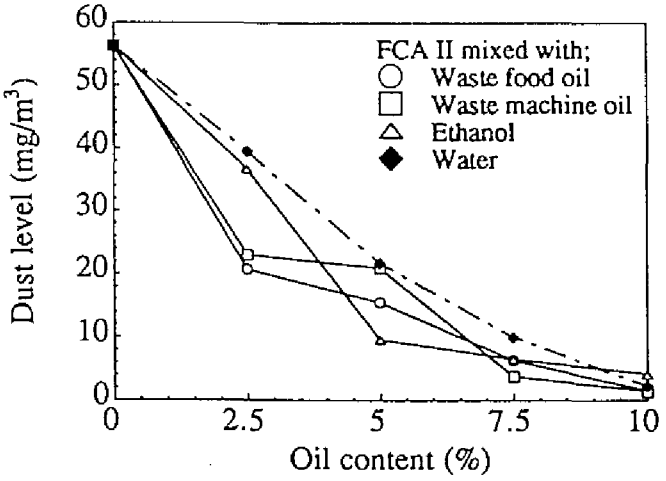


Fig. 2.5 Dust level of FCA

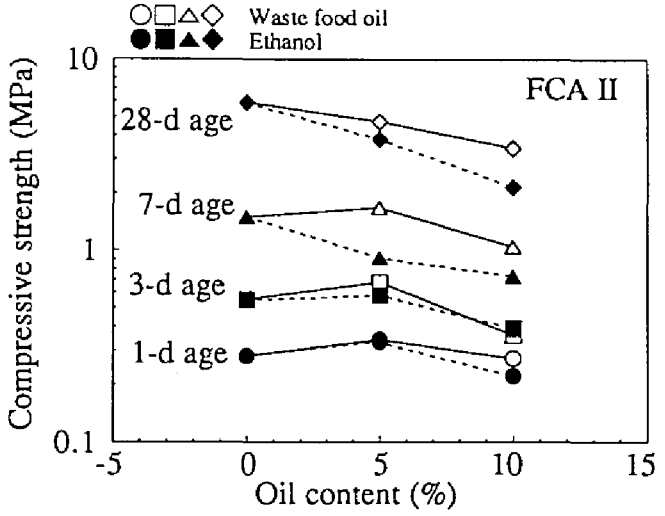


Fig. 2.6 Strengths of FCA mixed with oil

2.3.4 Application to Soft Soil Improvement

To evaluate the applicability of FCA to soft soil improvement, mixing tests were carried out on surplus soil of alluvial clay discharged from an underground excavation site. The clay soil used in the tests had a 93% liquid limit, a 34% plastic limit, and a 6.2 uniformity coefficient. The natural water content was 84%, and it was in a very soft clay condition. The preparation of the specimens was in accordance with the Practice for Making and Curing Noncompacted Stabilized Soil Specimens (JGS T 821-1990, which is equivalent to ASTM D1632).

In Fig. 2.7, even a 15% addition of FCA brought about the minimum compressive strength of 100 kPa, and therefore, the soil stabilized by FCA can be treated not as waste sludge but as useful soil material in accordance with the criteria established by the Japanese government for judging whether a material should be regarded as waste sludge or a recyclable soil, such as

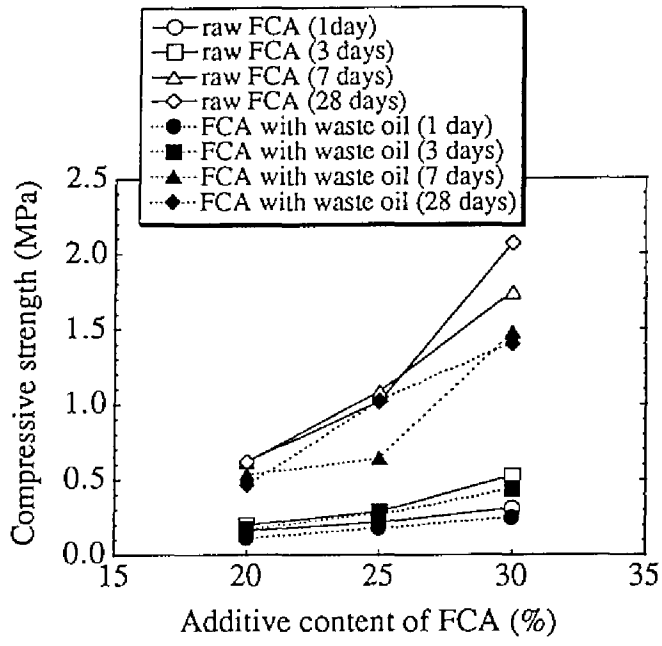


Fig. 2.7 Strengths of clay soil stabilized by FCA

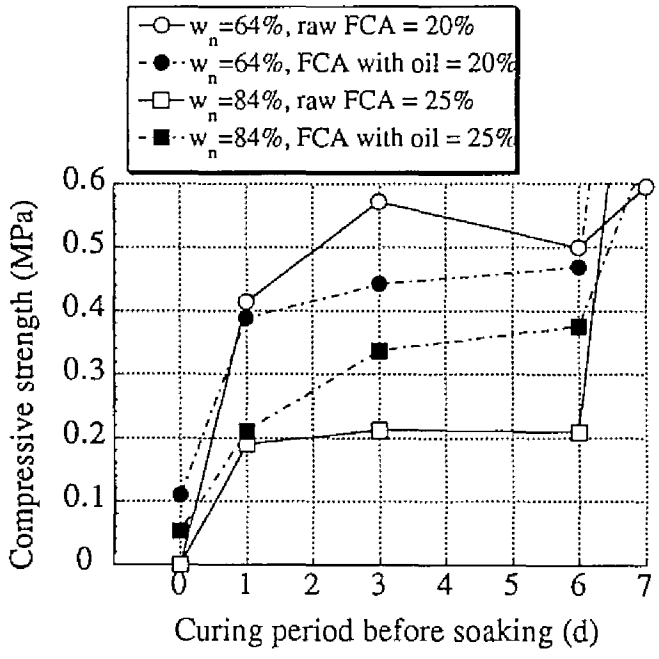


Fig. 2.8 7-day strengths of FCA stabilized soil

by a compressive strength of 0.5 kgf/cm^2 (= 49 kPa). With an additive content of 20%, the strength reached 1 MPa which is suitable for utilization not only in embankments or as subgrade, but also as subbase material. The additive content of FCA and the curing term affect the increase in strength, as is the case of an ordinary stabilizer, and the lime and the gypsum content of the FCA contribute to this strength development. The addition of FCA, treated by the "Non-Dusty Method," resulted in a slight deterioration in strength compared with the addition of raw FCA. This decrement is negligible, however, in terms of its applicability as a soil stabilizer.

Figure 2.8 shows the strengths of stabilized soil cured and soaked for 7 days. When it has soaked after over 1 day of curing, the FCA-stabilized soil retained a strength higher than 200 kPa. And the effect after soaking for 7 days was remarkable. The addition of FCA treated by the Non-Dusty Method conferred strengths of 100 kPa (w_0 = 64%) and 50 kPa (w_0 = 84%), while the soil samples would not harden with the addition of only raw FCA. Oil contributed to the development in strength under the above soaking conditions. This effect can be explained by the fact that oil may cover the soil and the FCA particles and prevent the particles from becoming excessively saturated. It can be concluded that the Non-Dusty Method extended the applicability of FCA to soft ground improvement.

2.3.5 Field Tests of Soil Stabilization by FCA

Case studies on the application of FCA to soft soil stabilization were performed. Raw FCA, not FCA treated by the Non-Dusty Method, was used in the studies. The objective was to improve the soft clay ground and construct a gravity-retaining wall and embankment, as shown in Figure 2.9. The original ground was a rice paddy field and soft enough to have a 2-6 SPT blow count from the surface to a depth of 9 m. The soil had a 69% liquid limit and a 32% plastic limit.

The ground improvement site, 5 x 20 m in width and 1 m in depth, was divided into four 5 x 5 m sections. The cement-based stabilizer ordinarily used was applied to two sections and a mixture of FCA and CAS was applied to the remaining two sections. As the performance was

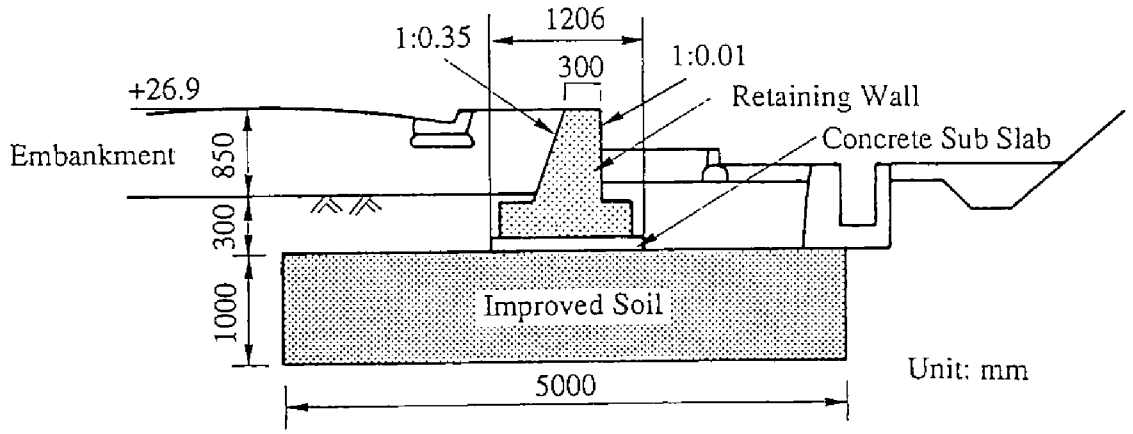


Fig. 2.9 Section of the construction site

Table 2.6 Test results from the construction site

Section	1	2	3	4
Design strength, q_u (kPa)	294	490	294	490
Type of stabilizer	CBS	CBS	FCA-a	FCA-b
Additive content (%)	3.5	4.9	13.3	11.7
Original ground				
Water content (%)	26.9	53.5	40.3	23.3
Cone index (kPa)	54	23	75	98
Follow-up examination				
Compressive strength (kPa)				
at 3 days	163	287	402	662
at 7 days	262	343	601	732
K_{30} (N/m^3)				
at 3 days	960	1372	1784	4724
at 7 days	1117	1254	2499	2097

Note: Design strengths were determined by the experimental results in soil with a 57% water content.
CBS, cement-based stabilizer;
FCA-a and FCA-b, mixtures of FCA I:CAS =7:3 and 5:5, respectively;
K_{30}, coefficient of subgrade reaction measured by the Plane Load Test on Soils for Road (JIS A1215-1980).

carried out experimentally, the required design strength was settled within 7 days at two levels, namely, 294 kPa and 490 kPa. The mixing ratio in the field, shown in Table 2.6, was determined based on the results of laboratory experiments. A back hoe with an exclusive dipper of a volume of 0.7m^3, executed the mixing work for 30 minutes and light compaction was achieved.

Table 2.6 also shows the results of a follow-up examination. As the condition of the original clay was not uniform, the test results cannot be evaluated as absolute comparison tests. However, the strength development of the soil materials stabilized by the FCA and CAS mixtures was remarkable, even when taking into account variations in the original ground. Samples from the sites treated with the cement-based stabilizer showed lower strength values than the sites which underwent the experimental treatment after 7 days of curing. The soils stabilized with FCA-CAS mixtures reached the design strength within 3 days. Over three years have passed since the execution, and there still have been no problems with either the embankment or the retaining wall.

2.3.6 Use for Solidification of Waste Sludge and MSW Fly Ash

The application of FCA to the solidification of waste sludge discharged from construction works and MSW fly ash has been proposed (Kamon and Katsumi 1994, Kamon et al. 1994). MSW fly ash stabilization by FCA will be discussed in Section 2.5, while waste sludge solidification will be described in Chapter 3, and the contents of which will therefore not be discussed in detail here.

2.4 Utilization of Stainless-Steel Slag (S-Slag) by Cement Hardening

2.4.1 Basic Properties of Materials

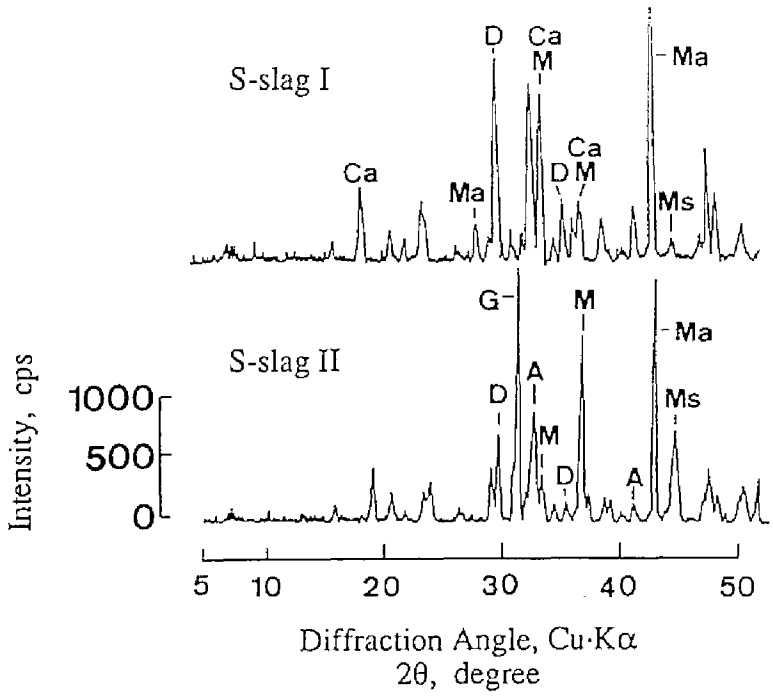
(1) S-slag

Two types of S-slag are used in this study, both of which are a kind of reducing electric furnace slag derived from different Austenitic Stainless-Steel Plants. The physical properties and the chemical compositions of the two materials are given in Table 2.7. The two types of S-slag are composed of fine grain particles equivalent in size to silt grains, and have a lower specific surface area (2025 cm^2/g and 2225 cm^2/g) than blast furnace iron slag (4000-4800 cm^2/g). The particle density (3.10 g/cm^3 and 3.19 g/cm^3) is within the limits of ordinary reducing electric furnace slag (2.80-3.25 g/cm^3).

The chemical composition of S-slag varies, but it mainly consists of oxides such as calcium oxide (CaO), silicon oxide (SiO_2), and aluminum oxide (Al_2O_3), which cause materials to possess latent hydraulic properties. The two kinds of slag have similar chemical compositions and are close in composition to average electric furnace reducing slag, except for the CaO content. The CaO content in general reducing slag lies in the range of 30% to 50%. The difference in CaO composition may be due to collecting spots and raw materials. Therefore, S-slag I and S-slag II used in this study are considered to represent reducing slag with rich and poor CaO contents, respectively. Regarding the slag efflorescence, the changes in volume when free-lime is hydrated to $Ca(OH)_2$ or the expansion for the formation of CSH (calcium silicate hydrate; $CaO \cdot SiO_2 \cdot H_2O$) and CASH (hydrated gehlenite; $CaO \cdot Al_2O_3 \cdot SiO_2 \cdot H_2O$), have been reported as possible causes (Kuwayama et al. 1992; Narita et al. 1978). A CaO content can influence the formation of $Ca(OH)_2$, CSH, and CSAH. These two materials are expected,

Table 2.7 Physical properties and chemical compositions of materials used

	S-slag I	S-slag II
Particle density (g/cm^3)	3.10	3.19
Grain size distribution (%)		
Sand fraction	0.0	0.0
Silt fraction	92.6	91.8
Clay fraction	7.4	8.2
Blaine specific surface area (cm^2/g)	2025	2225
Optimum moisture content (%)	-	30.5
Maximum dry density (g/cm^3)	-	1.72
Chemical compositions (%)		
SiO_2	22.4	19.4
Al_2O_3	9.8	11.4
CaO	45.6	30.2
Fe_2O_3	1.1	6.7
MgO	14.2	12.3
SO_3	0.2	0.8



M:Merwinite, D:Diopside, Ma:$MgO{\cdot}Al_2O_3$, Ms:β-$2MgO{\cdot}SiO_2$, Ca:$12CaO{\cdot}7Al_2O_3$, A:Alite, and G:Gehlenite.

Fig. 2.10 XRD patterns of S-slags

therefore, to have different hydraulic or efflorescence properties.

Figure 2.10 shows X-ray diffraction patterns for the two types of S-slag used. It has been reported that the main minerals of ordinary reducing electric furnace slag are dicalcium silicate ($2CaO{\cdot}SiO_2$), magnesium silicate ($2MgO{\cdot}SiO_2$), and calcium aluminate ($12CaO{\cdot}7Al_2O_3$), etc. (Kuwayama et al. 1992). Both kinds of slag exhibit peaks of merwinite ($Ca_3Mg(SiO_4)_2$), diopside ($CaMg(SiO_3)_2$), magnesium aluminum oxide ($MgO{\cdot}Al_2O_3$), and magnesium silicate (β-$2MgO{\cdot}SiO_2$). While S-slag I contains calcium aluminate ($12CaO{\cdot}7Al_2O_3$), S-slag II appears to contain alite ($3CaO{\cdot}SiO_2$) and gehlenite ($2CaO{\cdot}Al_2O_3{\cdot}SiO_2$), which are cement minerals.

Two types of S-slag were used in this study, namely, the raw material obtained from a factory and an S-slag finer than 0.425 mm. Such a slag is usually larger than 0.005 mm. Therefore, kaolinite was used to arrange the grain size distribution, and its particle size was finer than 0.005 mm. The kaolinite had a silt fraction of 15.8%, a clay fraction of 84.2%, a liquid limit of 84.7%, and a plastic limit of 35.1%.

(2) Hardening agent

As the hardening agent, Carbonated-Aluminate Salt (CAS) which is a cement-based stabilizer containing $Ca(OH)_2$, $Al_2(SO_4)_3$, and Na_2CO_3, is used. There are different kinds of CAS based on the mixing ratio. It has been previously shown that CAS is effective as a hardening material for soft clays or waste materials (Kamon et al. 1989; Tomohisa 1989; Nontananandh 1990).

The effects of the CAS materials have been summarized as

(1) the formation of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) and other reactional products and the crystallization of excess pore water in the soil;

(2) the activation of a pozzolanic reaction over a long term;

(3) the control of the pH value of the hardened mixtures; and

(4) the activation of hydration by accelerating the dissolution from soil/waste materials.

The composition of CAS used here is cement : $Ca(OH)_2$: $Al_2(SO_4)_3$: Na_2CO_3 = 50 : 30 : 15 : 5 (dry weight basis).

2.4.2 Experimental Procedure

The specimens were mixed and prepared in accordance with the Practice for Making and Curing Noncompacted Stabilized Soil Specimens (JGS T 821-1990). The cylindrical molds, 5 cm in diameter and 10 cm in length, were filled with fresh mixtures (after mixing for 5 minutes), and vibrated in order to remove air bubbles. The sealed specimens were cured at a constant room temperature of 20℃ with 80% relative humidity. In addition to the curing condition which is termed as *'Normal curing'*, the following curing process was performed for the durability tests, using specimens with three different mixed proportions which can gain strength in excess of 1 MPa in 1-day without yielding a loss in strength, after the specimens were cured under a constant room temperature for 6 days, and thereafter, cured in water for 1 day. The following steps were taken in curing the samples (Table 2.8):

(Drying and wetting test)

Table 2.8 Experimental conditions for the durability test

Items	Curing conditions	
	Drying	Wetting
Normal curing	sealed, 20±2℃, 80 % RH	
(Drying and wetting test)		
(1) Oven curing	electric furnace, 110±3℃	
(2) Drying(oven)-wetting	electric furnace, 110±3℃ 48 hours/cycle	water, 20℃ 24 hours/cycle
(3) 40℃ curing	electric furnace, 40±3℃	
(4) Drying(40℃)-wetting	electric furnace, 40±3℃ 48 hours/cycle	water, 20℃ 24 hours/cycle
(5) Drying(vacuum)-wetting	vacuum vessel, 20±2℃ 48 hours/cycle	water, 20℃ 24 hours/cycle
(Soaking test)		
2.5% Na_2SO_4 solution		2.5% Na_2SO_4, continuous soaking, 20℃
5% Na_2SO_4 solution		5.0% Na_2SO_4, continuous soaking, 20℃
5% $MgSO_4$ solution		5.0% $MgSO_4$, continuous soaking, 20℃

(1) The samples were cured in an electric furnace at 110℃, called *'Oven curing'*.

(2) They were dried in an electric furnace at 110℃ for a 48-hour cycle and stored in water for a 24-hour cycle, called *'Drying(oven)-wetting'*.

(3) The samples were cured in an electric furnace at 40℃, called *'40℃ curing'*.

(4) They were dried in an electric furnace at 40℃ for a 48-hour cycle and stored in water for a 24-hour cycle, called *'Drying(40℃)-wetting'*.

(5) The samples were dried in vacuum desiccators (made of 1 cm thick cylindrical plastic, 38 cm in inner diameter and about 50 cm in height with a steel cover plate at each end) for a 48-hour cycle and stored in water for a 24-hour cycle, called *'Drying(vacuum)-wetting'*.

(Soaking test)

Samples were stored in the following solutions:

2.5% Na_2SO_4, 5% Na_2SO_4, and 5% $MgSO_4$.

The temperature of the water and all the solutions was maintained at a constant 20℃. Unconfined compression tests and an X-ray diffraction (XRD) analysis were carried out after the curing period. A standard test method has not yet been established in Japan for durability under drying and wetting cycles. It has been reported that the durability of stabilized mixtures might be overestimated if they are dried at high temperatures (40-70℃), because such temperatures accelerate the hardening reaction (e.g., Kamon et al. 1990). In this study, a vacuum drying method, in which drying was performed with a suction pump (-750 mmHg) at a temperature of 20℃, was newly adopted to evaluate the durability in the early stages while maintaining a constant temperature.

2.4.3 Strength Characteristics of Stabilized S-Slag

Table 2.9 shows the compressive strengths of some S-slag mixtures. The proportions of the mixtures shown in Table 2.9 were determined so that the fresh mixtures would be workable enough to have the air bubbles removed from them by vibration and to avoid the occurrence of bleeding.

Table 2.9 reveals that CAS produces a greater hardening effect than ordinary Portland cement. For S-slag I, a marked gain in early strength was observed for mixtures with particle sizes smaller than 0.425 mm. This indicates that the strength development is affected by the particle size and the chemical composition of the metalloid pellets which remained in the S-slag. A decrease in strength is observed for many of the mixtures shown in Table 2.9. This is thought to be due to the efflorescence phenomenon. The mixtures without kaolinite clay, cured for 3 days, were approximately 40% lower in strength than the mixtures cured for 1 day (Fig. 2.11). However, if the mixtures are proportioned with some kaolinite (5% addition in this study), the strength of the S-slag mixtures can be maintained. Similar results were found in a study on the stabilization of incinerated pulp ash. The study indicates that the addition of kaolinite brings about effective stabilization due to a decrease in porosity and an acceleration in the formation of CSH (Kamon et al. 1991). For subbase purposes, it is recommended that the mixtures gain a

Table 2.9 Strengths of stabilized S-slag mixtures

		Material and mixing conditions			Compressive strength (kPa)			
Symbol	Type of stabilizer	Type of S-slag	Stabilizer content (%)	water/solid (%, by wt.)	1 day	3 days	7 days	28 days
MIX-1	Cement	Slag I	3	50	468	778	757	501
MIX-2	Cement	Slag I	6	50	549	733	574	432
MIX-3	CAS	Raw Slag I	3	45	1088	1041	956	*
MIX-4	CAS	Raw Slag I	3	50	2021	1337	1037	913
MIX-5	CAS	Raw Slag I	6	45	1290	1136	1089	*
MIX-6	CAS	Raw Slag I	6	50	1555	1332	1402	1321
MIX-7	CAS	Raw Slag I	9	50	1339	1739	1845	2418
MIX-8	CAS	Slag I	9	50	1987	1178	*	*
MIX-9	CAS	Slag I:K =95:5	9	50	1638	1859	1957	1859
MIX-10	CAS	Slag I:K =95:5	12	50	2263	2709	2631	2479
MIX-11	CAS	Slag II	3	35	392	601	1359	4218
MIX-12	CAS	Slag II	6	35	1675	2604	4868	8765
MIX-13	CAS	Slag II:K =95:5	3	35	316	568	1725	3125
MIX-14	CAS	Slag II:K =95:5	6	35	1591	3541	3855	4005

Note: 'K' stands for kaolinite clay, 'Raw Slag' for the untreated S-slag, and 'Slag' for S-slag finer than 0.425 mm. '*' stands for no data because of the failure of specimens.

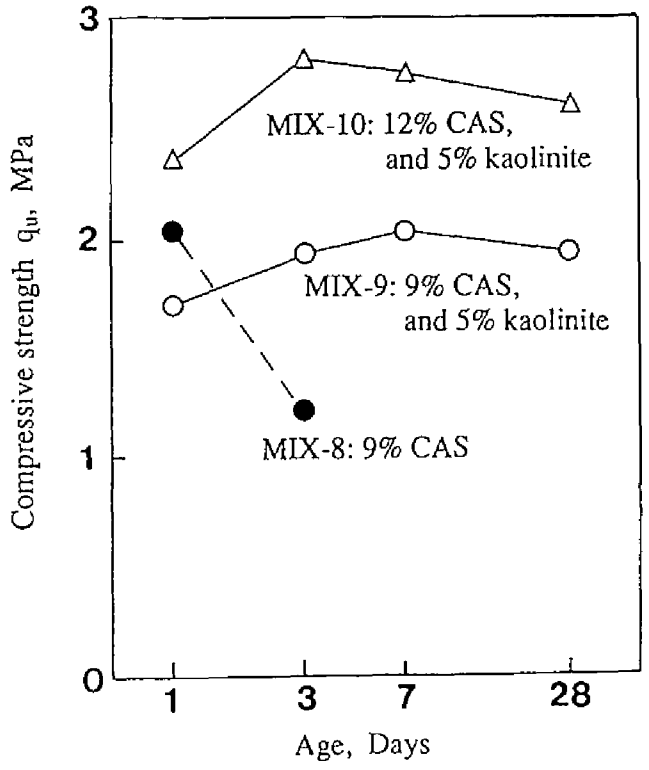


Fig. 2.11 Strength characteristics of S-slag I mixtures

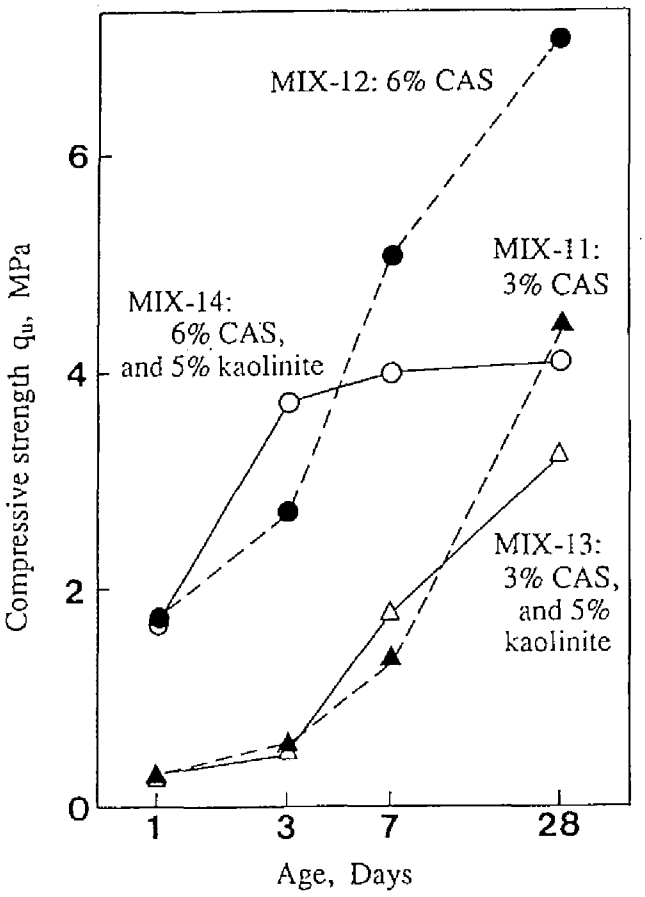


Fig. 2.12 Strength characteristics of S-slag II mixtures

14-day strength of more than 12 kgf/cm^2 (1.18 MPa), without yielding a loss in strength. Therefore, it is believed that an S-slag I mixture blended with CAS and kaolinite can be used as a subbase course material.

For S-slag II, the strength improved considerably with an increase in curing time when the mixtures were stabilized with CAS. And the addition of 6% CAS produced a higher strength than 1 MPa of compressive strength of the mixture cured for 1-day, while the mixture with a 3% addition of CAS produced a lower strength than only 500 kPa. In contrast to S-slag I, the addition of kaolinite to the Slag II mixtures was considered ineffective because it impaired the strength over a prolonged curing time. In Fig. 2.12, the mixtures with kaolinite showed a marked trend in the reduction of strength after approximately 7 days. Regarding their use as subbase materials, the mixtures with CAS are more important than those with the addition of kaolinite, and S-slag with a 6% addition CAS has potential for use.

Figure 2.13 shows the X-ray diffraction patterns of stabilized S-slag. The samples stabilized by ordinary Portland cement exhibit a formation of CSH hydrate. Both types of S-slag treated by CAS have remarkable peaks of CASH, as well as CSH, and the X-ray diffraction intensities of these hydrates also increase for mixtures which exhibit an increase in

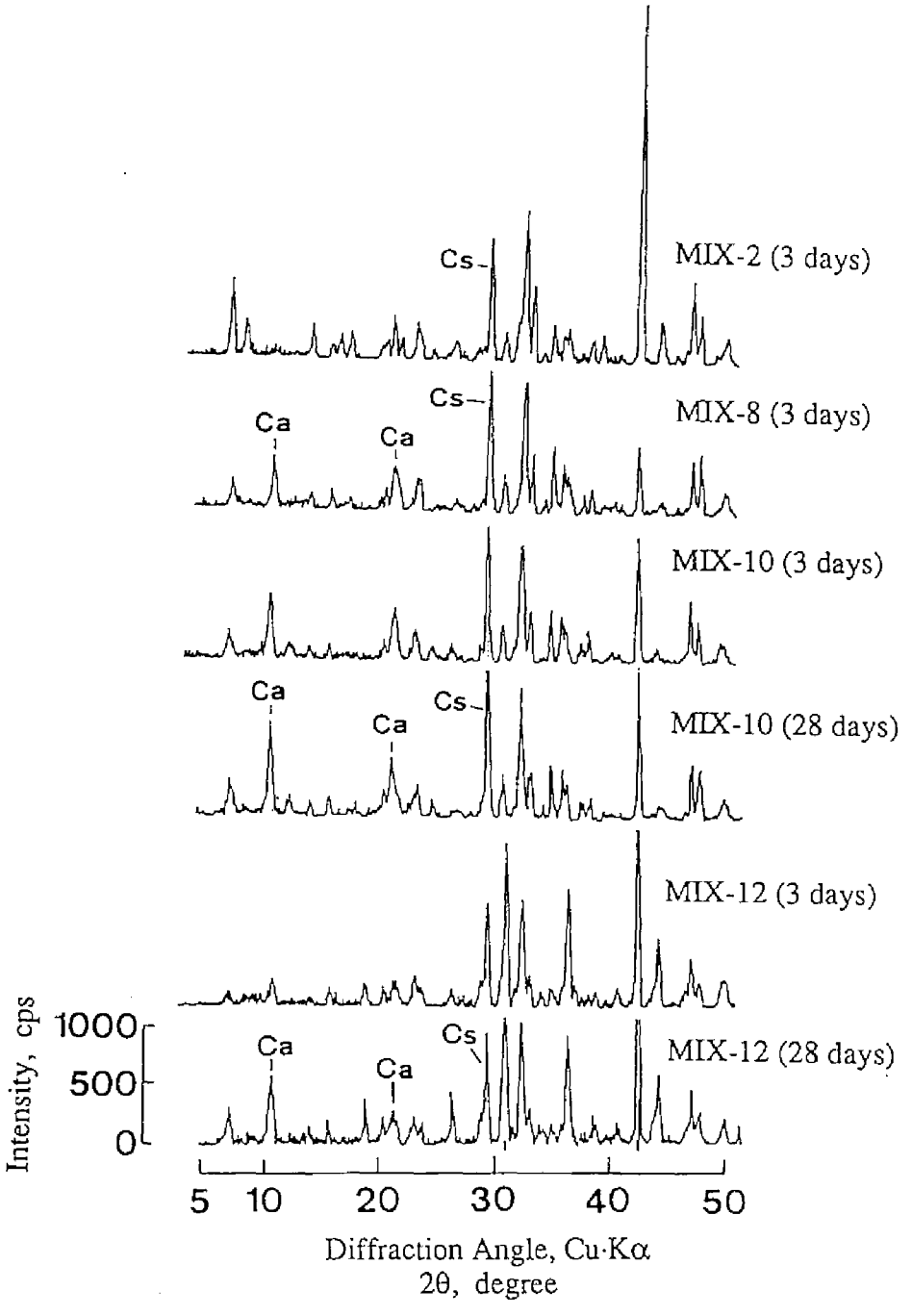


Fig. 2.13 XRD patterns of stabilized S-slag mixtures

strength over a prolonged curing time. The formation of CASH or CSH is very important when contemplating the efflorescence characteristics of S-slag. When stabilizing S-slag, however, CASH and CSH contribute to the strength development. It should be noted that the decrease in strength of many mixtures of S-slag I is not thought to be due to the formation of CSH or CASH, but to other reaction mechanisms.

2.4.4 Drying-Wetting Durability of Stabilized S-Slag

The confirmation of water removal by certain drying conditions is important to the evaluation of the curing methods proposed in this study. Figure 2.14 shows the weight change ratios for specimens under drying and wetting conditions, which indicate water removal and adsorption. The water removal ratio by a 40℃ drying method in 40℃ curing or *Drying(40 ℃)-wetting* is about 70% of the removal by 110℃ drying in *Oven curing* or *Drying(oven)-wetting*. The drying method with a temperature of 110℃ is unlikely to be effective in an in-situ environment, and it is known that soil near the surface of the ground often rises to 40℃. In Fig. 2.14, the

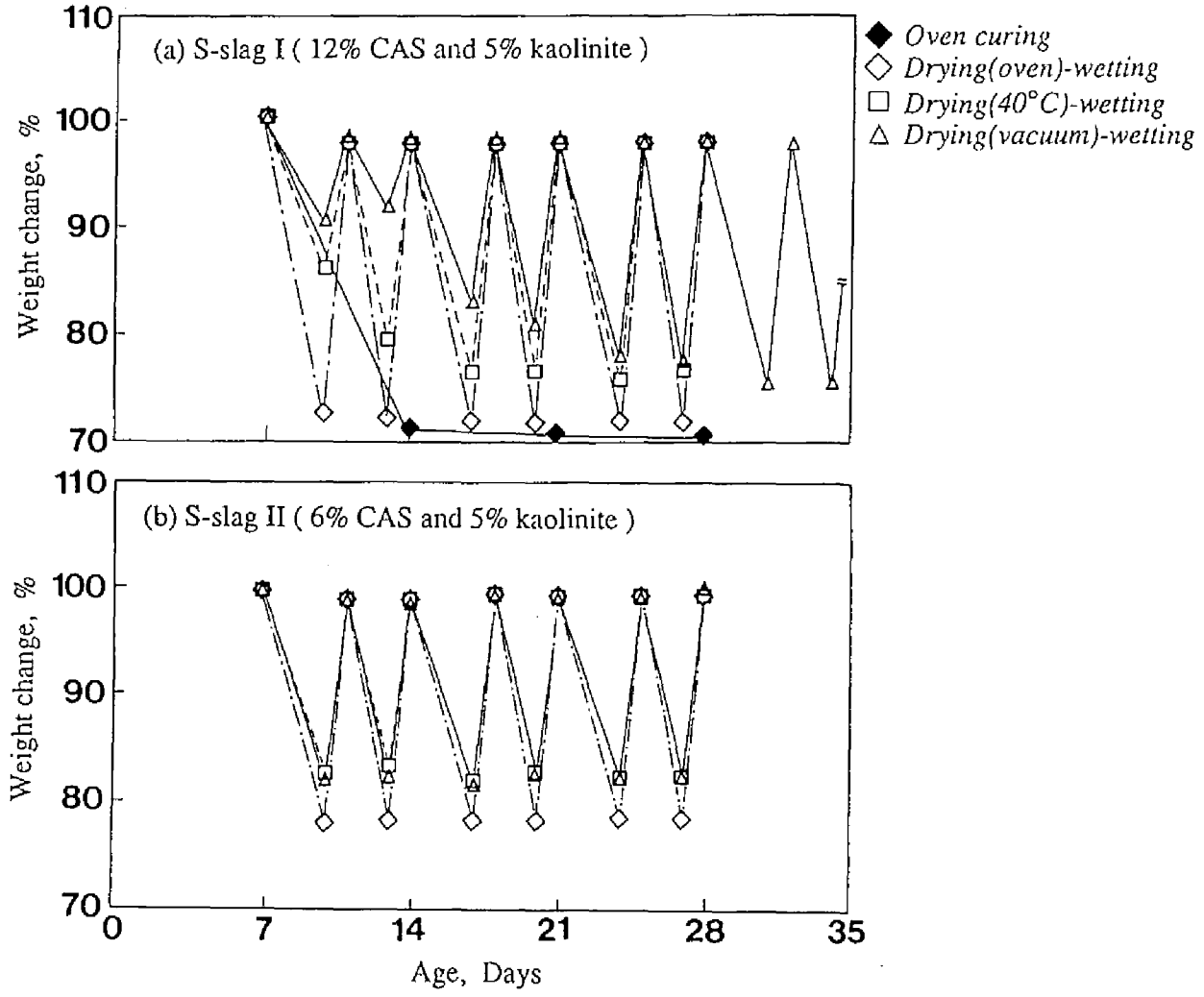


Fig. 2.14 Weight change of S-slag mixtures under drying-wetting

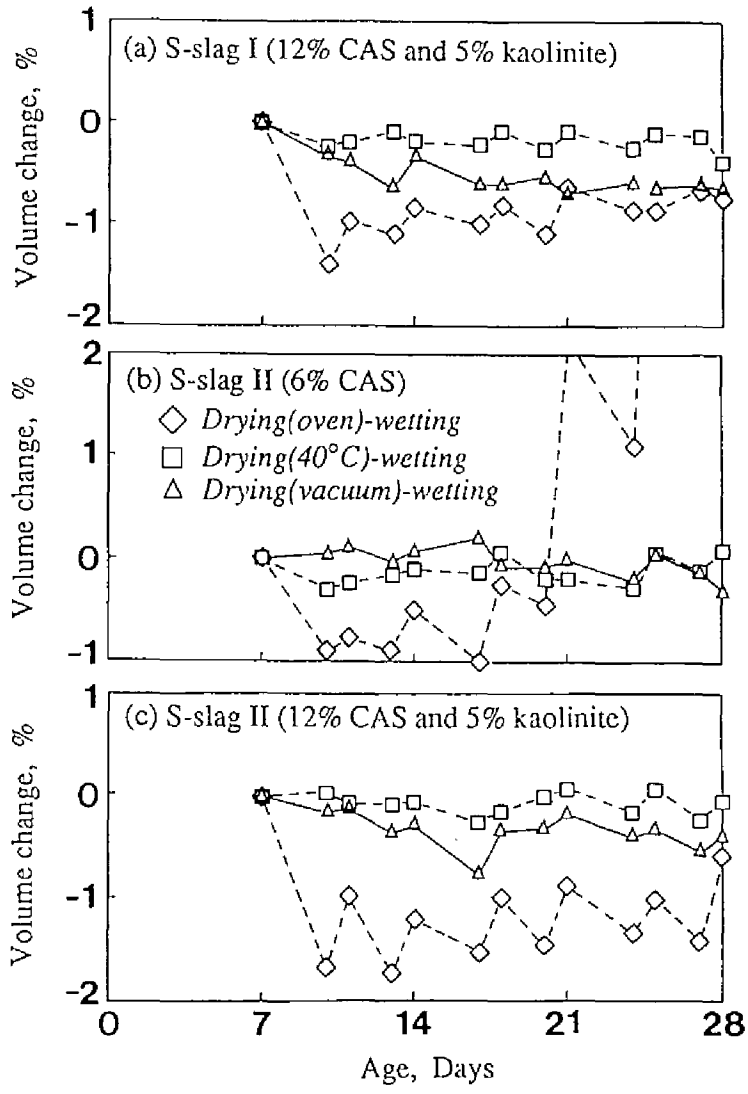
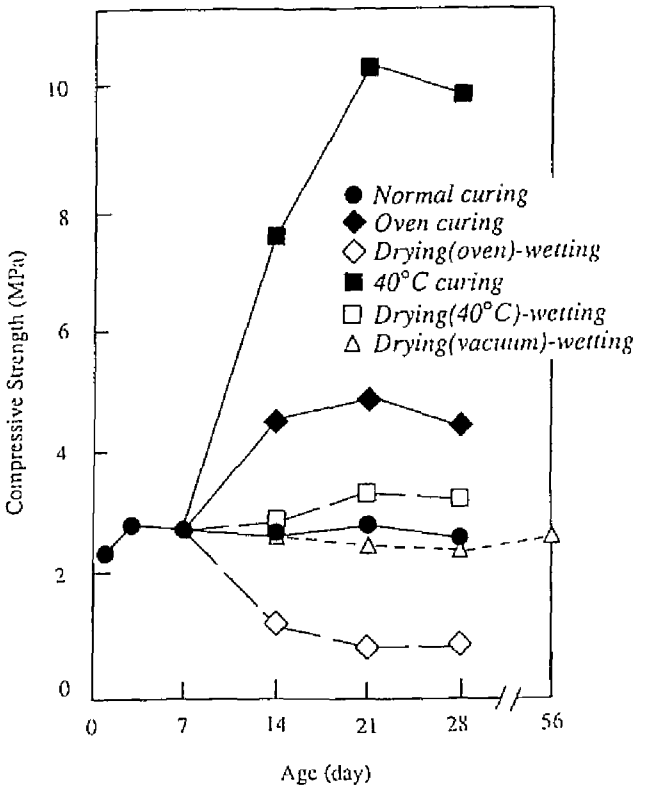


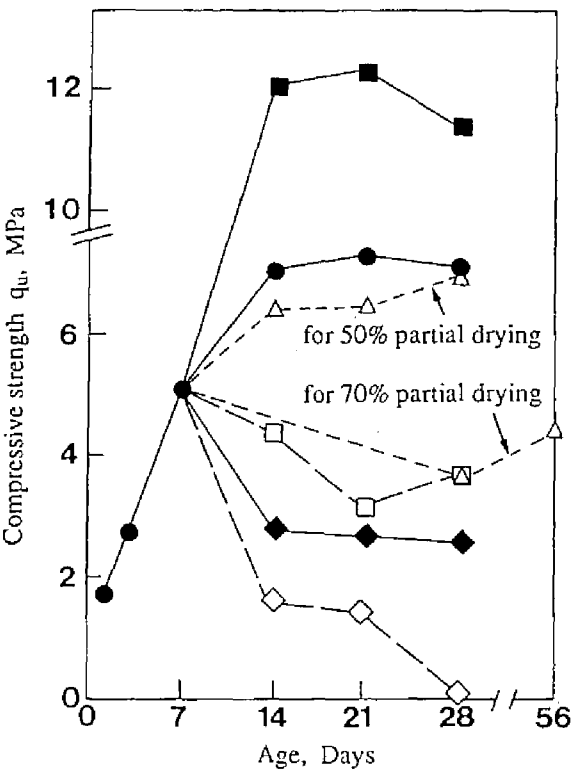
Fig. 2.15 Volume change of S-slag mixtures under drying-wetting

water removal ratio is comparatively low during the early cycles of *Drying(vacuum)-wetting*, because the number of samples in the vacuum desiccator affects the water removal. When the number of specimens in the desiccator is between 4 and 6, the dehydration ratio by vacuum drying is about 70%, which is approximately the same as that of the 40℃ drying methods. Thus, it is clarified that the newly adopted vacuum drying method is capable of the same water removal as in a 40℃ condition without raising the temperature.

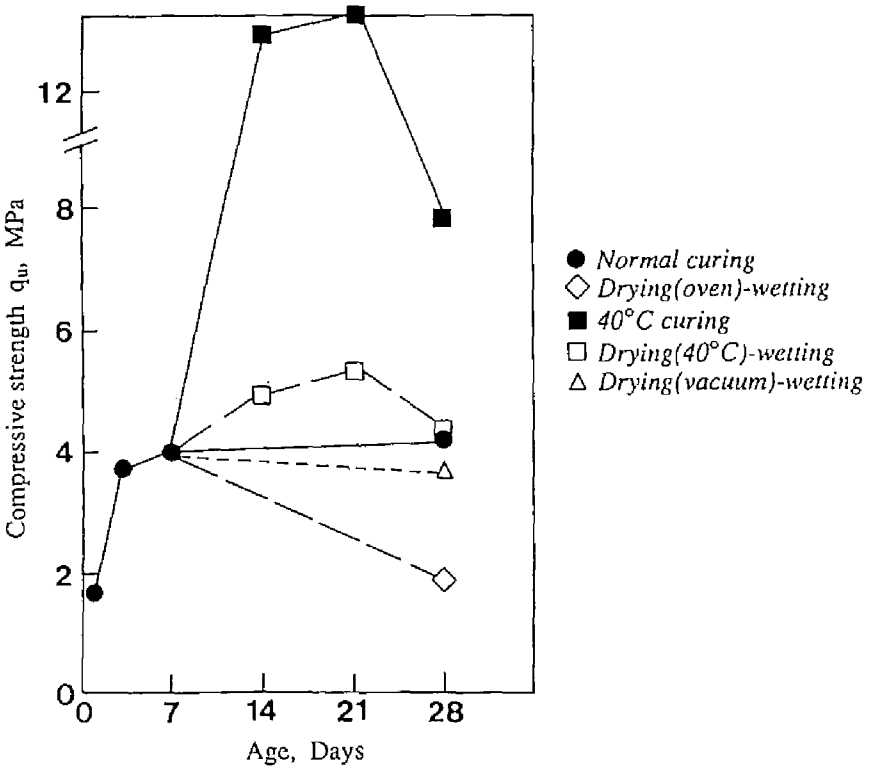
Volume changes of S-slag mixtures under drying-wetting conditions, as shown in Fig. 2.15, illustrate the affects of the drying method and the addition of kaolinite. For *Drying(vacuum)-wetting* and *Drying(40 ℃)-wetting*, shrinkage and swelling during each drying or wetting cycle are minute, and drying shrinkage ratios are less than 1% for all the cycles. For *Drying(oven)-wetting*, irreversible shrinkage occurred during the first drying, but afterwards a general tendency to swell was observed. Especially for S-slag II, without kaolinite, a marked



(a) S-slag I (12 % CAS and 5 % kaolinite)



(b) S-slag II (6 % CAS)



(c) S-slag II (6 % CAS and 5 % kaolinite)

Fig. 2.16 Change in strength with several curing conditions

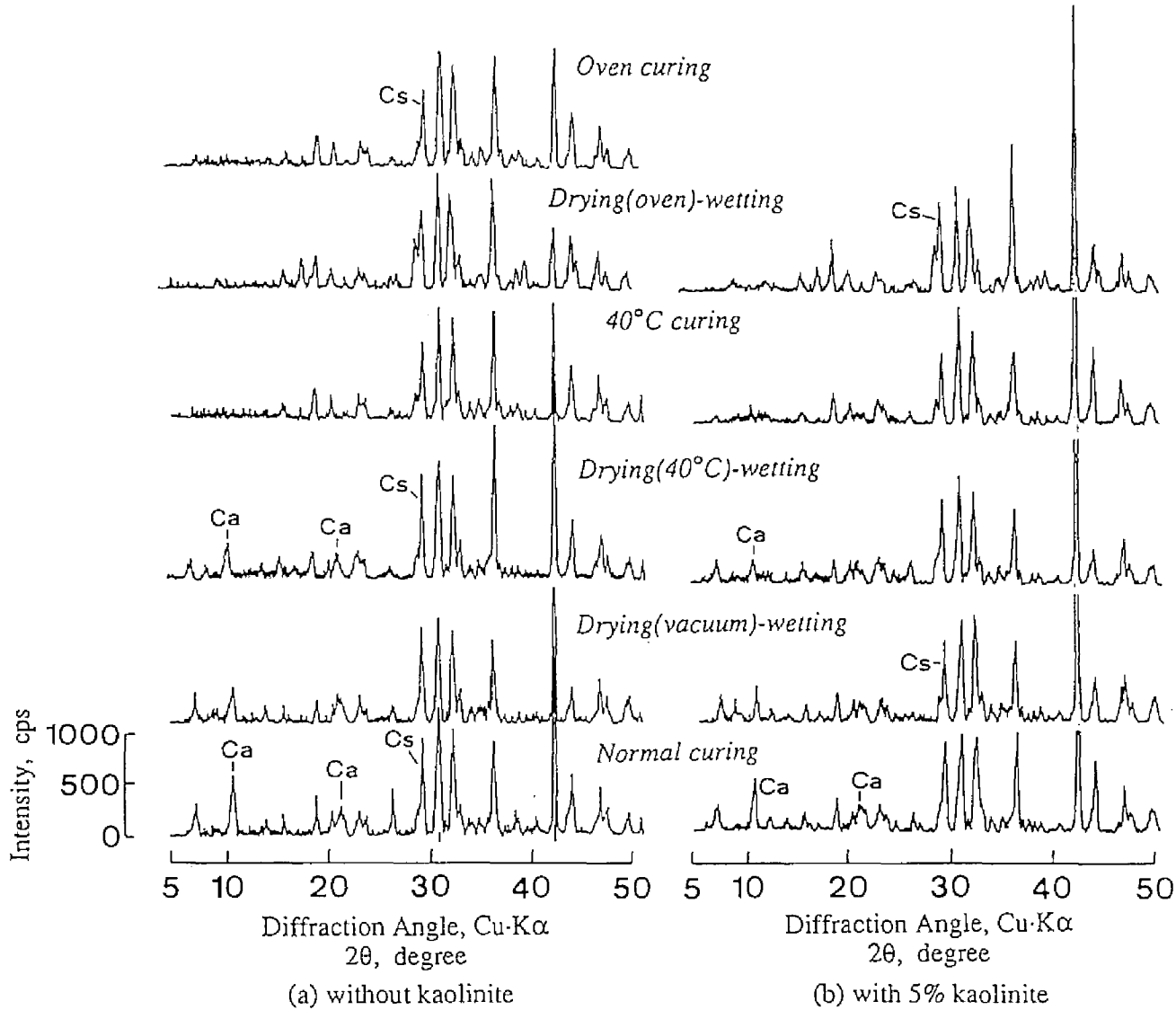


Fig. 2.17 XRD patterns of S-slag II mixtures with various curing conditions at 28-day curing

crack propagated and eventually led to failure.

Figure 2.16 illustrates changes in strength with respect to the curing period and the curing conditions. The compressive strength of specimens for a *40℃ curing* is as high as 10 MPa. This unusual increase in strength is the result of an increased tightness brought about by the drying and hardening reaction accelerated by high temperatures. *Drying(40℃)-wetting* and *Drying(vacuum)-wetting* are similar in their water removal ability and drying shrinkage characteristics, but differ obviously in their strength characteristics. In the case of *Drying(40℃)-wetting*, the S-slag mixtures without kaolinite have only half the strength of mixtures with *Normal curing* after 28 days (6 cycles), while the mixtures with kaolinite clay show high strength when compared to mixtures with normal-curing. In the case of *Drying(vacuum)-wetting*, the strength of the mixtures with or without kaolinite shows a reduction by 10-20% and 50%, respectively, when compared with *Normal curing*. As the 40℃-drying is nearly equal to the Vacuum-drying in drying shrinkage, it is thought that the development of strength for *Drying(40℃)-wetting* is caused by the acceleration of the hardening reaction with high temperatures. The strengths of stabilized S-slag I with kaolinite and S-slag II without kaolinite, obtained from *Oven curing*, are two and a half times as high as the strengths for *Normal curing* (Fig. 2.16 (a) and (b)). S-slag mixtures with kaolinite obtained from *Drying (oven)-wetting* do not show any remarkable expansion and/or failure, and maintain a strength of about 1 MPa. Therefore, the durability of mixtures shows more dependence on the existence of clay minerals and curing conditions than on the type of S-slag used or the water content in the mixture. It is inferred that the S-slag with CAS materials and kaolinite clay can potentially be used as a subbase course material.

Figure 2.17 shows the X-ray diffraction patterns for S-slag mixtures under several curing conditions. As stated above, CSH and CASH are considered to be main reaction hydrates which contribute to the strength development. While the peaks of CSH are unchangeable for the different curing conditions, those of CASH are due to the drying and wetting cycles. CASH was not detected in the specimens for *40℃-curing* and *Oven curing*. For *Drying(40℃)-wetting*, CASH appeared again when the sample was rewetted, but consequently, a greater reduction in CASH was observed than with *Normal curing*. For *Drying(oven)-wetting*, CASH did not reappear when the specimens were rewetted. These phenomena can be the signs of dehydration and re-hydration of the water of crystallization. For *Drying(vacuum)-wetting*, CSAH seems to be sensitive to drying-wetting, but the addition of kaolinite restrains the decline of CSAH. Considering the stability of the hydrate compounds which play a role in strength development, kaolinite leads to an improvement in durability.

2.4.5 Soaking Durability of Stabilized S-Slag

An assessment of the durability against sulfate attacks is of great importance if these materials are to be used as earthen materials. Figure 2.18 shows the strength characteristics of specimens cured over a long period by *Normal curing* and in a 2.5% Na_2SO_4 solution. The deterioration in

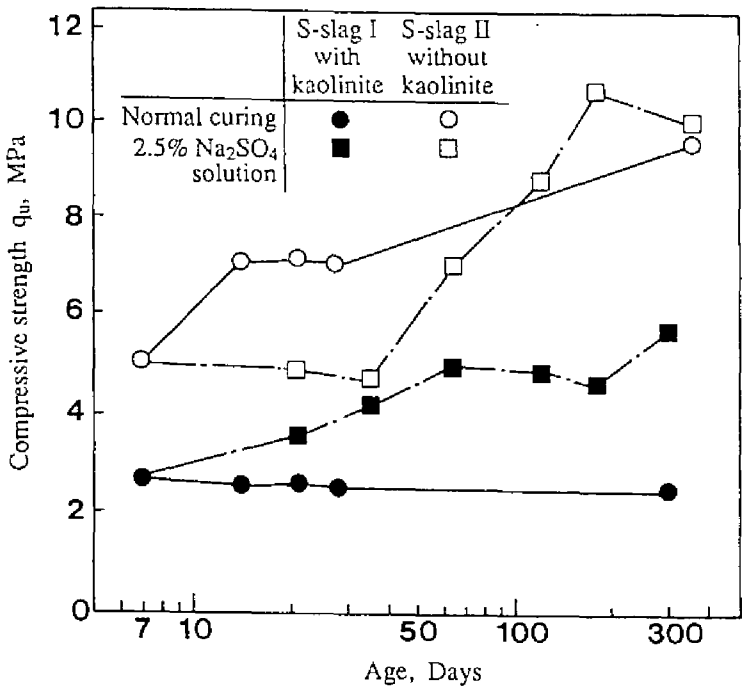


Fig. 2.18 Strength-time curves of S-slag mixtures

strength of both S-slag mixtures does not appear over a long period of time. The S-slag cured in an Na_2SO_4 solution has a much higher strength than the slag cured by *Normal curing*. X-ray diffraction patterns exhibit the formation of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) in these specimens, as shown in Fig. 2.19. On concrete and concrete-like materials, it is generally known that the formation and subsequent expansion of hydrated ettringite causes the deteriorative expansion of mixtures for certain concentrations of certain kinds of sulfate solutions (Mehta 1973). This deteriorative phenomenon is due to the type and concentration of sulfate, the chemical and physical properties of the stabilized materials, the characteristics of the mixtures, and the curing term. The test conditions in this study do not lead to a decrease in strength. The changes in weight over time for specimens stored in sulfate solutions and in water are presented in Fig. 2.20. The specimens stored in 2.5% sulfate solutions show only slight changes in weight over time and remain in excellent condition after a soaking period of one month. It is evident that the specimens stored in an extremely high concentration of sulfate solution undergo marked changes in total moist weight and exhibit signs of deteriorative expansion. Specimens in 5% $MgSO_4$ showed poor sulfate crystallization on the surface and specimens in 5% Na_2SO_4 were badly cracked, while those stored in water remained in good condition as shown in Photo 2.3. One must be aware that the resistance of stabilized S-slag to sulfate attacks depends on the curing conditions.

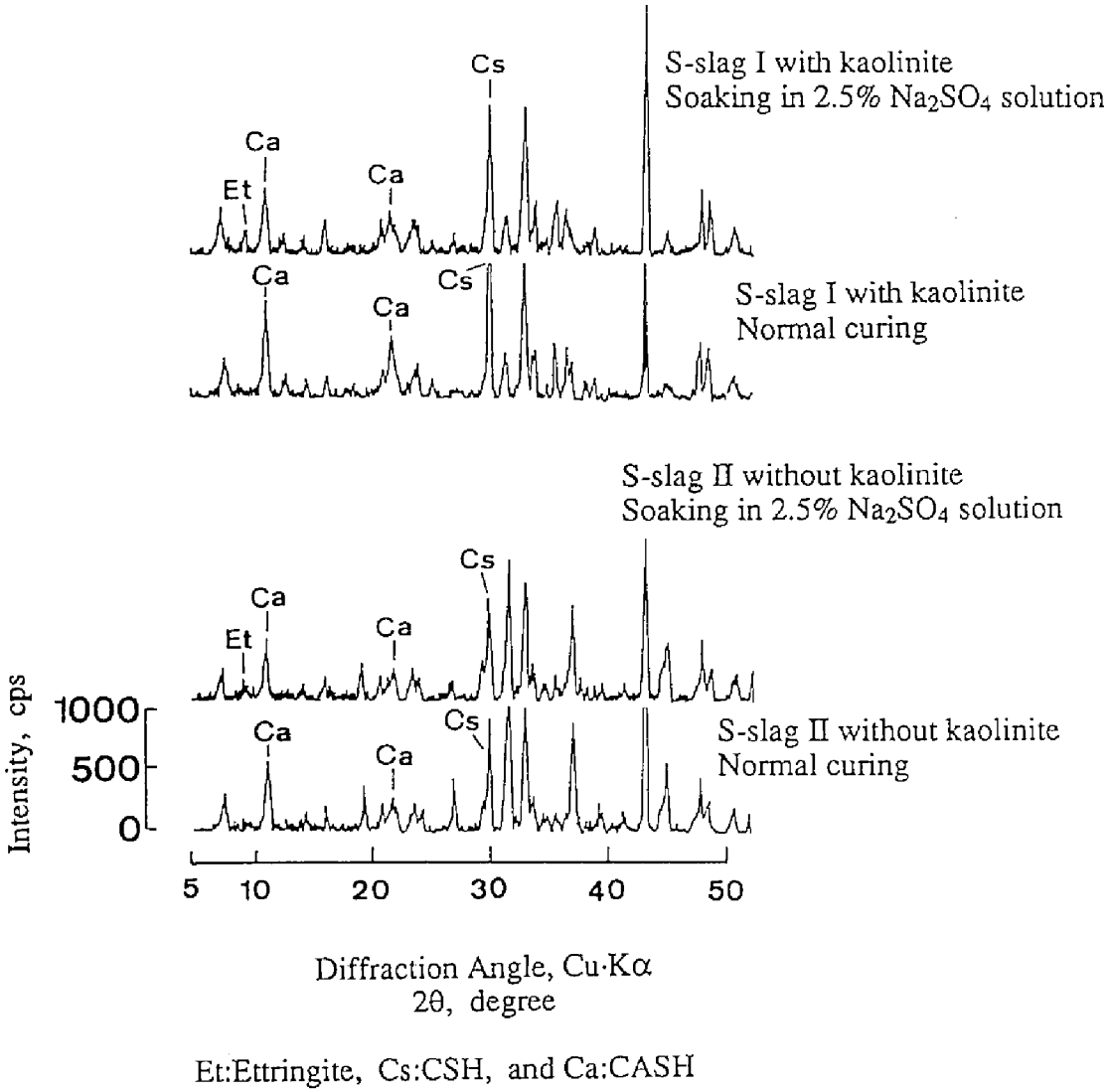


Fig. 2.19 XRD patterns of S-slag mixtures with soaking condition

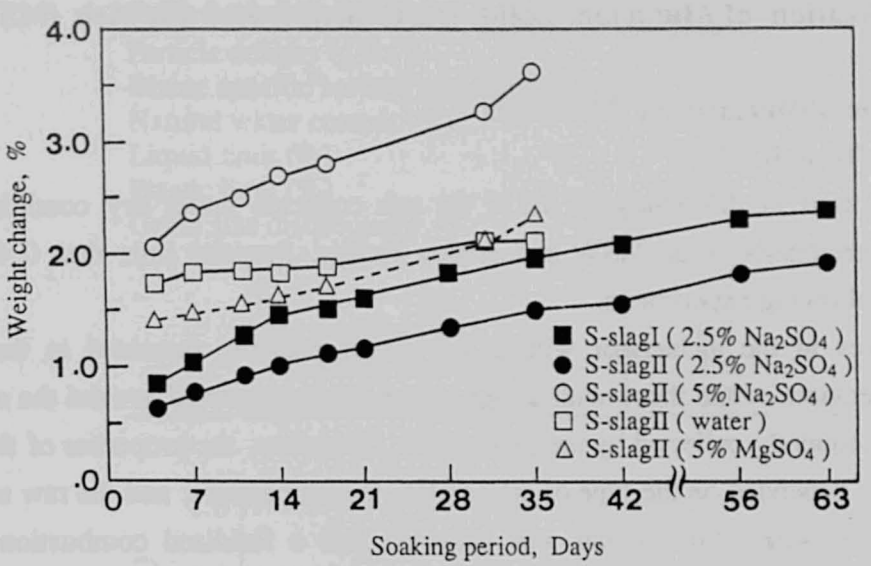
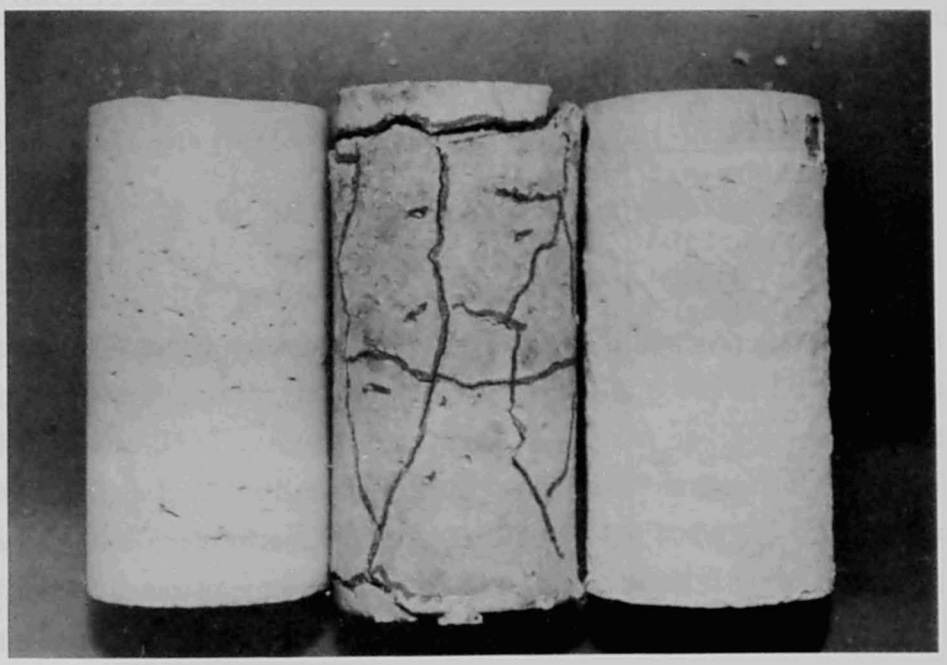


Fig. 2.20 Weight changes of S-slag mixtures with soaking conditions



(a) (b) (c)

Photo 2.3 5-month-aged stabilized S-slag II stored in:
(a) water, (b) 5 % Na_2SO_4 solution, and (c) 5 % $MgSO_4$ solution

2.5 Stabilization of Municipal Solid Waste Incinerated Fly Ash (MSW Fly Ash)

2.5.1 Basic Properties of Materials

(1) MSW fly ash

The material used in this study is MSW fly ash collected under dry conditions from the electrostatic precipitator of an MSW incineration facility. Particles finer than 0.425 mm were used for the following experiments.

Substances in the incinerator with a low vapor pressure remained in the bottom ash through incineration, while those with a high vapor pressure moved toward the exhausted gas and were consequently collected by the precipitator. Therefore, the properties of the bottom ash and the fly ash depended on the type of incinerator, the temperature, and the raw materials. The incinerator from which the fly ash was collected was a fluidized combustion type whose incineration temperature was in the range of 800-1000℃.

The chemical composition and leachate components of the MSW fly ash are shown in Tables 2.10 and 2.11, respectively. The salt concentration and the electric conductivity were measured according to the sodium-ionic electrode method and the alternating current method, respectively. Of the electropositive elements, most of the silicon (Si) and aluminum (Al) remained in the bottom ash, while heavy metals such as cadmium (Cd), plumbum (Pb), arsenic

Table 2.10 Chemical composition of MSW fly ash

Cd (mg/kg)	225
Pb (mg/kg)	3750
Zn (mg/kg)	21000
T-Cr (mg/kg)	235
As (mg/kg)	67
T-Hg (mg/kg)	4.5
Fe (mg/kg)	1650
Cu (mg/kg)	1800
PCB (mg/kg)	< 0.05
Ca (%)	9.5
S (%)	4.1
Cl (%)	13.0
N (%)	0.01

Table 2.11 Leachate components of MSW fly ash

Cd (ppm)	10.4
Pb (ppm)	19.6
Zn (ppm)	11.0
Cr(VI) (ppm)	0.03
As (mg/kg)	ND
pH	6.5
Salt concentration (%)	1.1
Electric conductivity (mS/cm)	12.7

Table 2.12 Physical properties of MSW fly ash

Particle density (g/cm^3)	3.03
Blaine specific surface area (cm^2/g)	107
Natural water content (%)	1.28
Liquid limit (%)	35.0
Plastic limit (%)	N.P.
Grain size distribution	
Sand fraction (%)	95.8
Silt fraction (%)	4.1
Clay fraction (%)	0.1
Uniformity coefficient	1.6
Coefficient of curvature	0.8

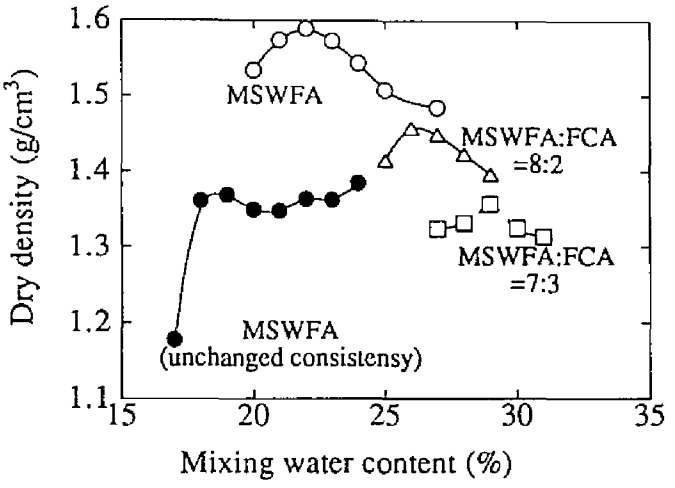


Fig. 2.21 Compaction curves of MSW fly ash

(As), mercury (Hg), and potassium (K) were detected in the fly ash more than in the bottom ash due to their low vapor pressure. In particular, as the boiling points of Cd and Hg are very low, namely, 767℃ and 357℃, respectively, most of the Cd and Hg were concentrated and contained in the fly ash. Cd, Pb, and Zn leach in high concentration from the used ash, which can not satisfy the environmental criteria established for landfilling by the Environmental Agency, Japan. Another important characteristic of the materials is the salt contents. The MSW fly ash consisted of a high composition of NaCl and KCl.

Table 2.12 exhibits the physical properties of the MSW fly ash. It mainly consists of sand particles and its uniformity coefficient of 1.6 makes it too low to be compacted properly. Figure 2.21 shows the compaction curves of the fly ash. If the ash is mixed with water for a long time, the fresh mixture can exhibit high consistency, similar to the FCA presented in Section 2.3.2. However, changes in consistency have a different effect on the fly ash mixed with water than on the FCA. For the MSW fly ash, change in consistency resulted in an increase in both the optimum water content and the maximum dry density, while changes in consistency for FCA lead to a decrease in just the optimum water content. This phenomenon is thought to be caused

Table 2.13 Physical properties and chemical composition of FCA

Particle density (g/cm^3)	2.09	Chemical compositions (%)	
Blaine specific surface area (cm^2/g)	2850	SiO_2	29.6
Grain size distribution		Al_2O_3	19.9
Sand fraction (%)	7.6	CaO	13.0
Silt fraction (%)	80.0	Fe_2O_3	3.2
Clay fraction (%)	12.4	SO_3	3.1
Ignition loss (%)	18.0	C	14.8

Table 2.14 Mix proportions of stabilizers used

	Cement	$Al_2(SO_4)_3$	$Ca(OH)_2$	FCA
Cement	100	-	-	-
Stabilizer A	90	5	5	-
Stabilizer B	20	5	5	70
FCA	-	-	-	100

by the behavior of soluble salts. In other words, the salts can dissolve when mixed with water and the mixture can consequently be compacted of high densities.

(2) Fluidized bed combustion coal fly ash

Fluidized bed combustion coal fly ash (FCA) was used in experiments as an additive agent for the stabilization of MSW fly ash. The basic properties of FCA are shown in Table 2.13. This FCA was collected at the same facility as FCA I, presented in Section 2.3, but it has a different composition from FCA I because the time at which it was collected was different.

2.5.2 Experimental Procedure

Cylindrical specimens were prepared for unconfined compressive strength tests, soaking durability tests, the X-ray diffraction (XRD) analysis, scanning electronic microscope (SEM) observations, and leachate tests. The specimens were mixed and prepared in accordance with the Practice for Making and Curing Compacted Stabilized Soil Specimens Using Rammer (Standard of the Japan Cement Association, CAJS L-01-1990). The specimens were sealed and cured under a constant room temperature of 20℃, with a relative humidity of 80%. The mixing time and water content were determined based on the compaction characteristics stated in Section 2.5.1 (1), in order to achieve the change in consistency of the fresh mixtures.

The procedure for the leachate tests affected the test results. In particular, the longer agitation time caused the encapsulation of heavy metals (Tomizawa et al. 1979, Tanaka et al. 1992). In this study, the leachate tests were carried out with the method originally proposed. The 30 g samples were crushed to smaller than 2 mm in diameter after unconfined compressive strength tests, and were mixed with 300 g of water. The filtrate was analyzed by an atomic absorption spectrophotometer after a 5-minute agitation. Leachate tests established for landfilling by the Environmental Agency in Japan, were also performed on some specimens.

2.5.3 Stabilization of MSW Fly Ash by Cement Hardening

Four types of stabilizers, namely, cement, cement-based stabilizers A and B, and FCA were

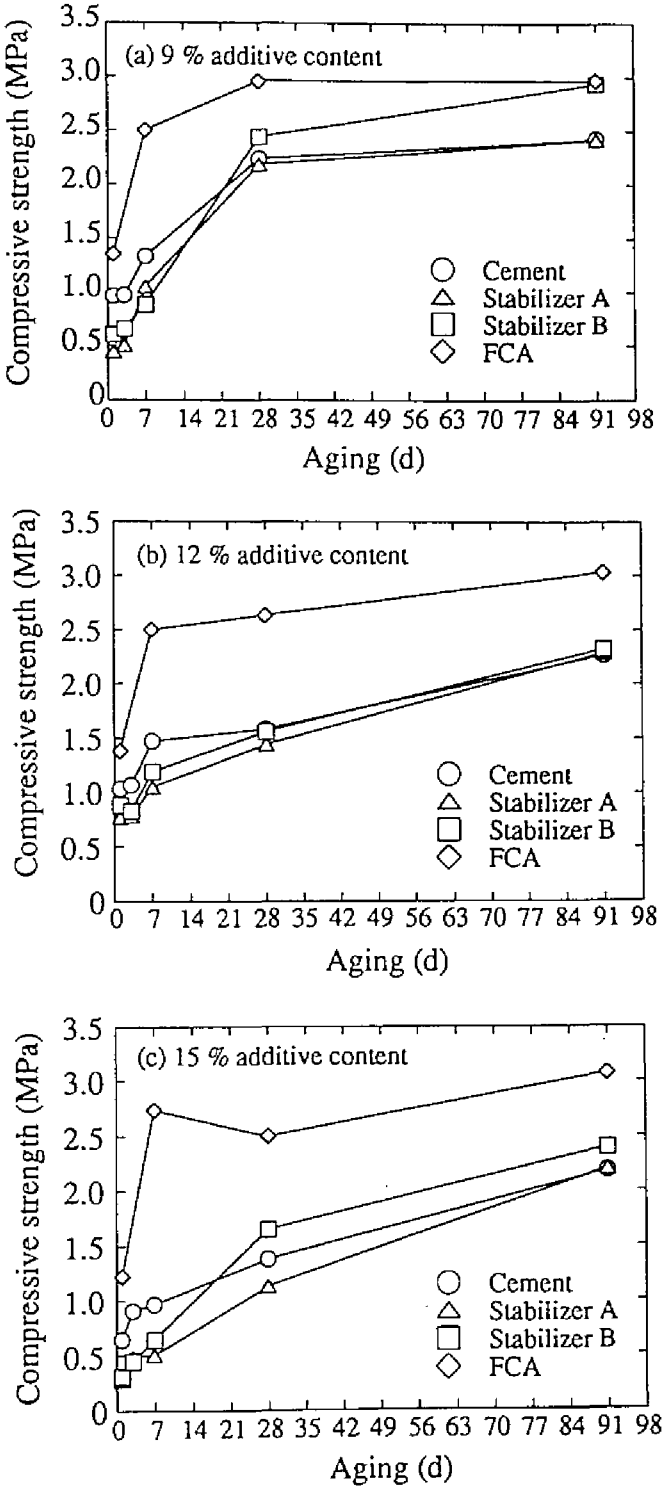


Fig. 2.22 Strengths of hardened MSW fly ash

assessed for the stabilization of MSW fly ash, and are shown in Table 2.14. To prepare the specimens in accordance with the Practice for Making and Curing Noncompacted Stabilized Soil Specimens (JGS T 821-1990), the water content was set at 22% and fresh mixtures were mixed up for 6 minutes before compaction.

(1) Strength development

Figure 2.22 shows the strength characteristics for the stabilized MSW fly ash. The FCA differs remarkably from the other stabilizers (cement and cement-based stabilizers) in its contribution to strength development. If stabilizers containing cement are used, the increase in strength will continue over a long period of curing (13 weeks), while the MSW fly ash stabilized by FCA can achieve a higher strength than 2 MPa in the early stages (one week). The strength increase after 7 days is not at all remarkable. The MSW fly ash stabilized by FCA has a higher strength than the fly ash stabilized by other stabilizers in each additive content and in each curing period. The effect of the additive content on the strength development can not be shown.

According to the results of the X-ray diffraction analysis shown in Fig. 2.23, no possible by-products due to ordinary cement hydration can be identified except for a small amount of ettringite, while NaCl and KCl were detected at high intensities. In the SEM photos (Photo 2.4),

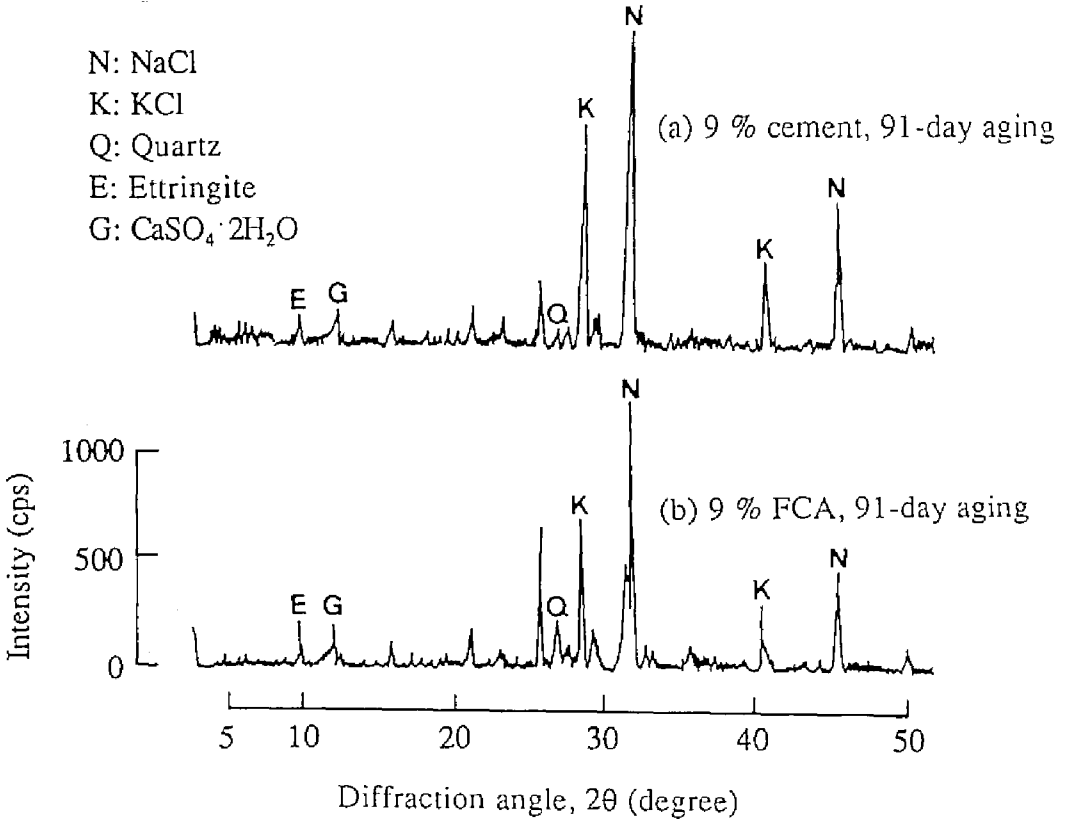
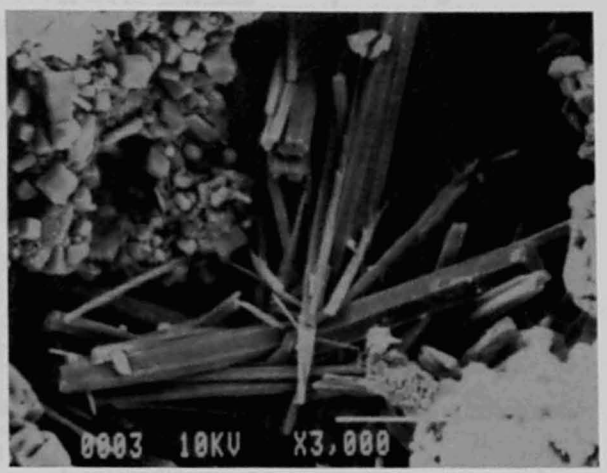


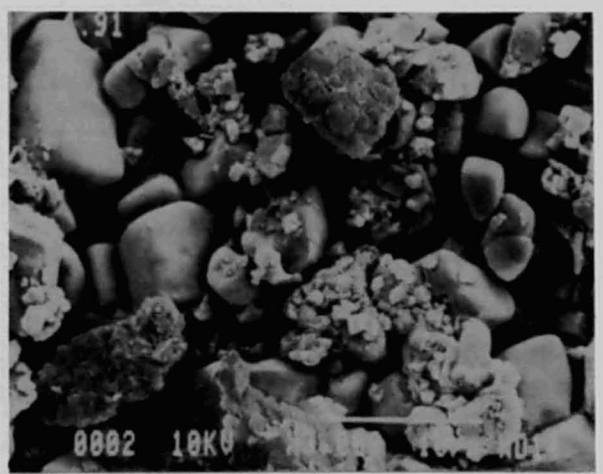
Fig. 2.23 XRD patterns for stabilized MSW fly ash

(a) 9 % cement



(b) 9 % cement, pore volume

(c) 9 % stabilizer A



(d) 9 % FCA

Photo 2.4 SEM micrographs of hardened MSW fly ash at 91-day curing

the crystals with parallelepiped or a ring shape were widely spread throughout the observed area. The needle-shaped crystals existed only in the pore volumes between the crystals. An X-ray micro analyzer identified these parallelepiped, ring-shaped, and needle-shaped crystals as NaCl, KCl, and ettringite, respectively.

From these test results, the hardening mechanisms can be summarized as follows: Soluble substances, NaCl and KCl, which do not solve during mixing, form a skeleton. As cement and FCA adsorb the pore water due to hydration, the chemical deposition of the solved NaCl and KCl contribute to the formation of the skeleton, but cover the cement or the FCA to prevent the cement from hydration. FCA is thought to contribute much more to the chemical deposition caused by the water adsorption ability than cement or cement-based stabilizers, and consequently, it attains a higher hardened strength.

(2) Leachate characteristics of heavy metals

The behavior of heavy metals such as Cd, Pb, and Zn, contained in the MSW fly ash, should be addressed. The leachate characteristics, which were obtained through the experimental method stated in Section 2.5.2, are presented in Table 2.15.

FCA differs from other stabilizing agents in its Cd leachate characteristics as well as its strength development. While Cd leachate from the specimens containing cement is lower than 0.1 ppm, in spite of the kind of stabilizer or the curing period involved, high leachate concentrations of Cd were detected in the ash stabilized with FCA, especially in the early stages of curing, and the Cd leachate criteria (0.3 ppm) for harmful heavy metals, set down for landfilling by the Environmental Agency, can be achieved only after curing for longer than 7 days. The Cd leachate is closely related to the pH of the solutions, as shown in Fig. 2.24.

Table 2.15 Leachate components of hardened MSW fly ash (9% additive content)

Type of stabilizer	Aging (d)	pH	Leachate concentration (ppm)			Salt concentration (%)	Electric conductivity (mS/cm)
			Cd	Pb	Zn		
Cement	7	9.0	0.14	0.14	ND	1.3	27
	28	9.1	0.08	0.19	ND	1.4	26
	91	9.7	0.06	0.28	ND	1.4	23
Stabilizer A	7	9.3	0.09	0.14	ND	1.4	27
	28	9.6	0.07	0.12	ND	1.4	25
	91	9.4	0.05	0.20	ND	1.5	27
Stabilizer B	7	9.3	0.11	0.14	ND	1.2	25
	28	9.6	0.09	0.14	ND	1.1	25
	91	9.6	0.07	0.18	ND	1.1	24
FCA	7	9.0	0.31	0.13	ND	1.4	25
	28	8.9	0.29	0.18	ND	1.3	22
	91	9.1	0.13	0.13	ND	1.0	23

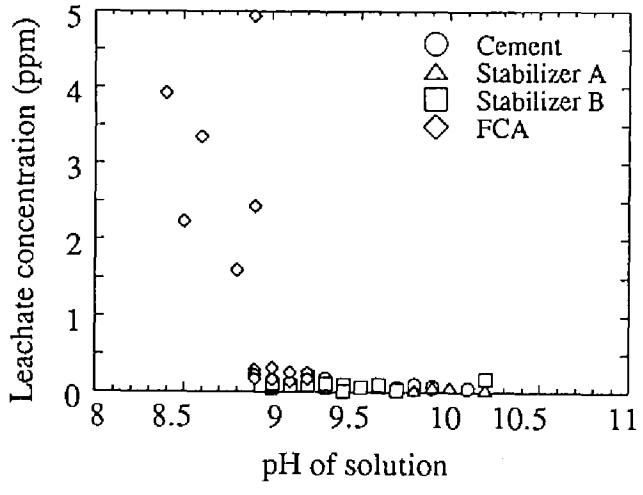


Fig. 2.24 Leachate concentration of Cd versus pH of solution

Table 2.16 Leachate components of hardened MSW fly ash by soaking

Type of stabilizer	Aging (d)	pH	Salt concentration (%)	Electric conductivity (mS/cm)
Cement	7	9.1	1.1	2.5
	28	9.3	1.1	23
	91	9.3	1.1	21
Stabilizer A	7	9.4	1.2	24
	28	9.5	1.1	24
	91	9.6	1.1	23
Stabilizer B	7	9.1	1.2	25
	28	9.5	1.2	22
	91	9.0	1.1	21
FCA	7	9.0	1.1	23
	28	9.1	1.2	24
	91	9.4	1.0	23

According to these results, if the leachate solution has a lower pH value than 9.0, the Cd leachate must be dealt with seriously. As an alkaline environment is required for the containment of Cd, 1 week of curing is needed when using FCA as the stabilizing agent.

The leachate of two other components, Pb and Zn, was not affected by the kind or the additive content of the stabilizer or by the curing period. Zn is thought to become as stable as $Zn(OH)_2$, and consequently, is not detected. The levels of Pb leachate cleared enough of the leachate criteria established for landfilling by the Environmental Agency.

(3) Soaking durability

Since hardened mixtures of MSW fly ash consist of soluble substances such as NaCl and KCl, but not the cement hydrated by-products from the XRD analysis and SEM observations, their durability under soaking conditions should be assessed from environmental and geotechnical viewpoints. A series of soaking tests were therefore performed.

The hardened mixtures of MSW fly ash with cement or a cement-based stabilizer gradually failed due to soaking and turned into particles. However, MSW fly ash stabilized with FCA was able to maintain its hardened shape under soaking conditions, even though cracks and/or fractures were observed after 7 days of soaking. Table 2.16 shows the chemical properties of the water in which the samples were soaked. Hardened 30 g samples were soaked in 300 g of water after aging. As the effects of the type of stabilizer can not be confirmed by electric conductivity and/or the salt concentration of the soaked water, the mechanisms of soaking durability can not be explained only in terms of salt leachate. Other effects on the durability will be presented in the next section.

2.5.4 Application of Coal Fly Ash to Stabilization of MSW Fly Ash

Previously in Section 2.5.3, it was stated that FCA affects only the strength development and the soaking durability but not the Cd containment. Both cement and the cement-based stabilizer

Table 2.17 Mixing proportions for stabilization of MSW fly ash

Symbol	Mixing ratio			Mixing water content
	MSW fly ash	FCA	Cement	(%)
M-13	80	20	0	26
M-14	80	20	5	26
M-15	80	20	10	26
M-16	70	30	0	29
M-17	70	30	5	29
M-18	70	30	10	29

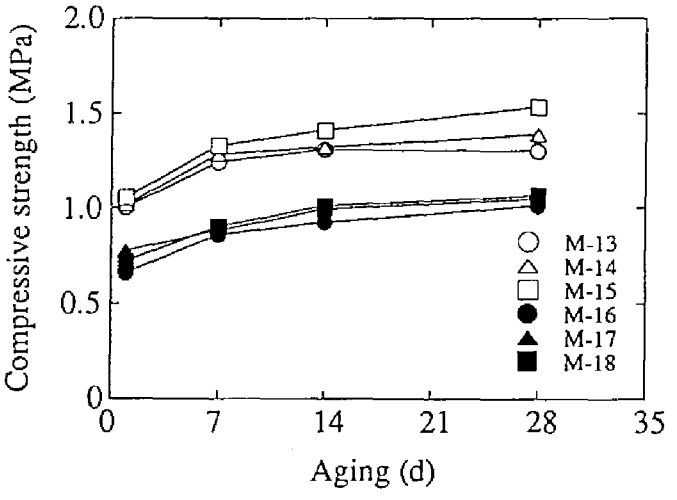


Fig. 2.25 Strength characteristics of stabilized MSW fly ash

have an effect on the Cd containment, while cement hydration can not be seen. Therefore, the single use of these stabilizers is limited, while the multiple use of them can be considered. The effects of using both cement and FCA is discussed in this section. The mixing proportions are shown in Table 2.17, where the mixing water contents were determined by the compaction characteristics exhibited in Fig. 2.21.

(1) Strength development

The high strength development of the specimens was observed due to compaction, as shown in Fig. 2.25. The compressive strength depended on the FCA content; lower contents of FCA caused higher strengths from these results previously presented in Fig. 2.22. As the aging time and the cement content have little affect on the strength increase, it is thought that the hydration of cement components can not contribute to the hardening mechanisms. From the X-ray diffraction analysis, NaCl and KCl were detected in large quantities and ettiringite was observed in small quantities. This is similar to the MSW fly ash stabilized singly by cement or by FCA.

(2) Leachate characteristics of heavy metals

Leachate concentrations of heavy metals are shown in Table 2.18. The Cd leachate correlates to the pH value, similar to that in Section 2.5.3. Therefore, the Cd could leach in high concentrations if FCA was used without cement. The criteria to assess the Cd leachate is judged

Table 2.18 Leachate components of hardened MSW fly ash

Symbol	Aging (d)	pH	Leachate concentration (ppm)		
			Cd	Pb	Zn
M-13	1	8.3	4.49	0.38	0.17
	7	9.0	0.26	0.18	ND
	14	8.8	0.20	0.17	ND
	28	9.3	0.17	0.24	ND
M-14	1	9.9	0.08	0.15	ND
	7	9.5	0.08	0.18	ND
	14	9.8	0.08	0.26	ND
	28	9.7	0.05	0.25	ND
M-15	1	10.1	0.08	0.14	ND
	7	9.7	0.07	0.13	ND
	14	9.7	0.05	0.25	ND
	28	9.9	0.05	0.23	ND
M-16	1	9.3	3.05	0.29	0.11
	7	9.0	0.27	0.17	ND
	14	9.4	0.20	0.17	ND
	28	9.2	0.20	0.23	ND
M-17	1	10.1	0.06	0.20	ND
	7	9.7	0.06	0.17	ND
	14	9.6	0.06	0.18	ND
	28	9.8	0.04	0.22	ND
M-13	1	9.9	0.06	0.19	ND
	7	9.7	0.05	0.17	ND
	14	9.7	0.04	0.14	ND
	28	10.0	0.02	0.27	ND

Table 2.19 Leachate components of hardened MSW fly ash by leachate tests set by the Environmental Agency, Japan

Symbol	pH	Leachate concentration (ppm)				
		Cd	Pb	Zn	Cr(VI)	As
M-13	9.8	0.08	0.33	0.03	ND	ND
	10.1	0.03	0.16	0.02	ND	ND

to be 9.0 in the pH value of the solution. The leachate characteristics of Pb and Zn are also similar to those in the case separately stabilized by FCA and by cement. The multiple use of FCA and cement achieved the containment of heavy metals.

Table 2.19 shows the leachate test results obtained by the method noticed by the Environmental Agency, Japan. All test results cleared the leachate standard for landfilling.

(3) Soaking durability

The hardened strength of the MSW fly ash, stabilized with FCA and cement, decreased due to soaking, but remained high enough to be used as a geotechnical filling material, as shown in Fig.

Table 2.20 Leachate components in the soaked water

Symbol	Soaking period (d)	pH	Leachate concentration (ppm)		
			Cd	Pb	Zn
M-14	1	9.7	<0.005	0.02	ND
	6	9.3	0.01	0.03	ND
M-17	1	9.9	ND	ND	ND
	6	9.6	<0.005	0.03	ND

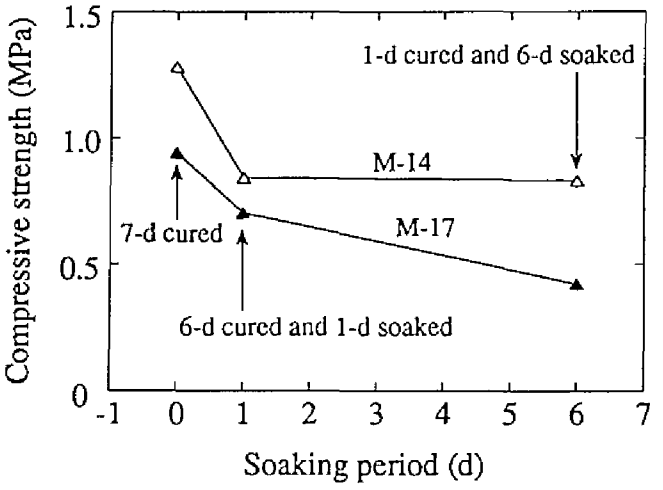


Fig. 2.26 Strength changes of stabilized MSW fly ash due to soaking

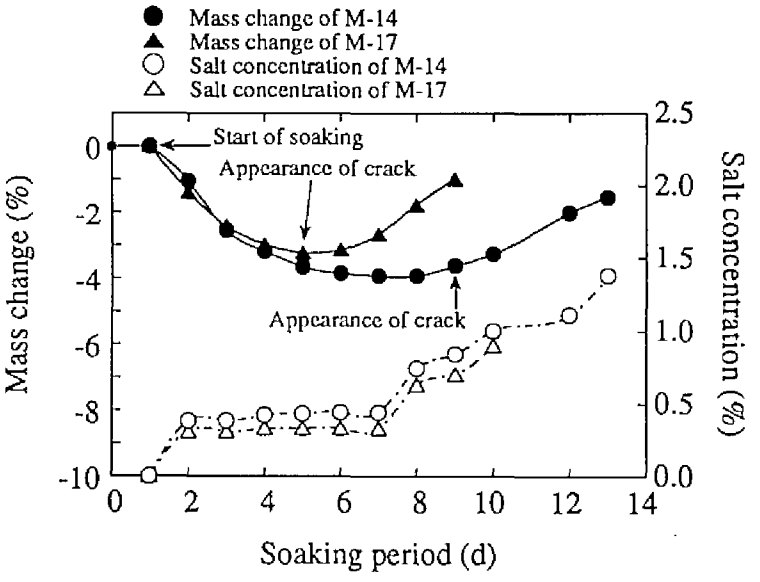


Fig. 2.27 Mass change of stabilized MSW fly ash and salt concentration of soaked water

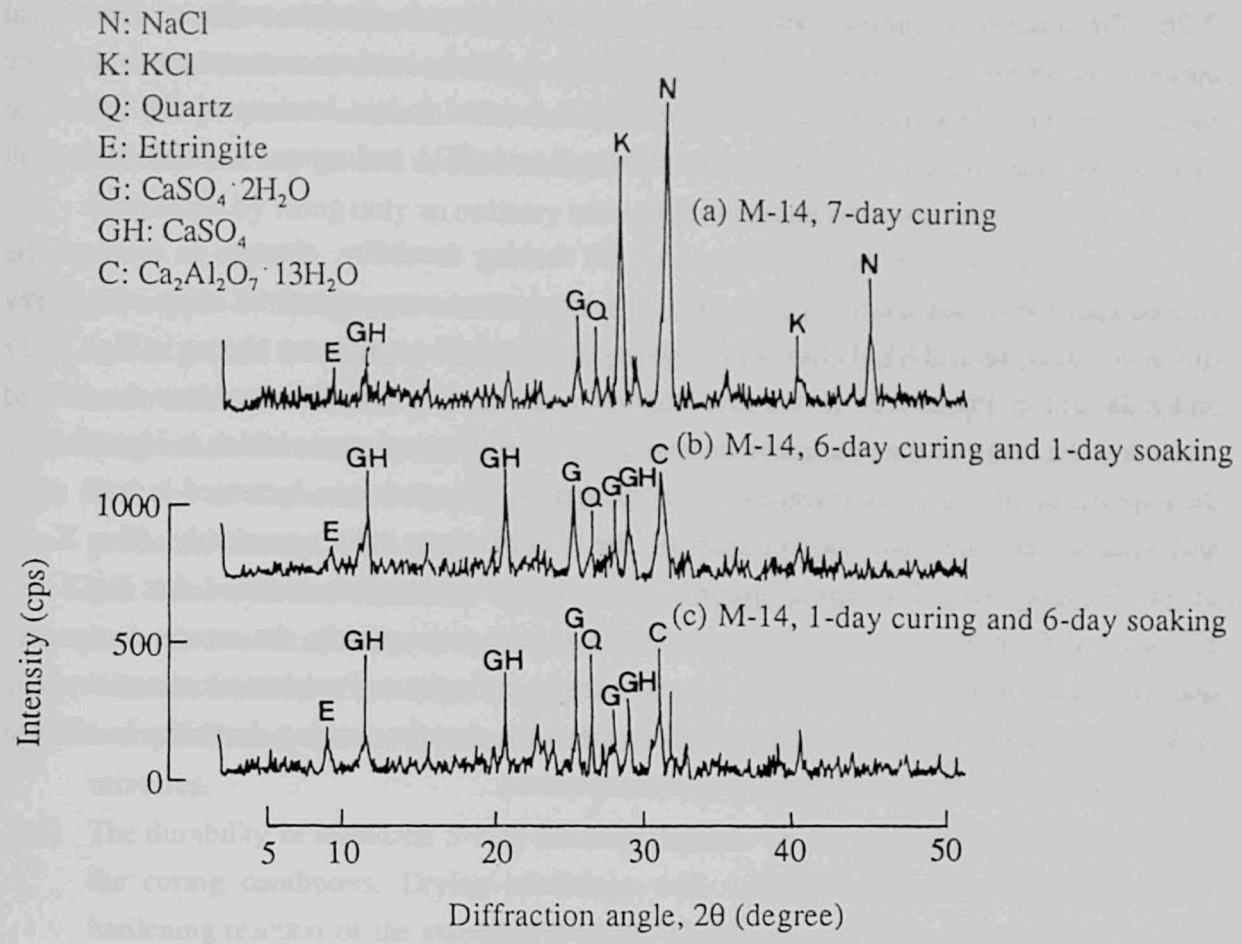
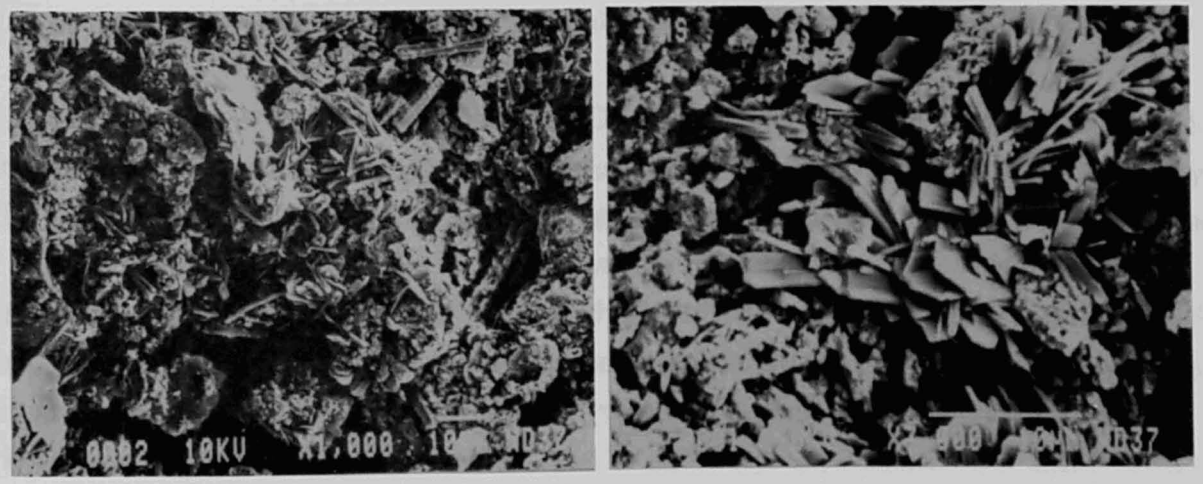


Fig. 2.28 XRD patterns for MSW fly ash mixtures under soaking condition



M-17, 1-day curing and 6-day soaking

Photo 2.5 SEM micrographs of hardened MSW fly ash under soaking conditions

2.26. The leachate of heavy metals into the soaked water is another major environmental concern. According to the test results shown in Table 2.20, the leachate concentrations of heavy metals were very low and a longer soaking period resulted in less leachate of Cd. It can be summarized, therefore, that MSW fly ash stabilized with FCA and cement is stable in landfill sites regardless of the groundwater conditions.

In order to evaluate the mechanisms of the soaking durability, changes in mass of the soaked specimens and the salt content of the soaked water were measured. Also, the X-ray diffraction analysis and SEM observations were conducted. The results are shown in Figs. 2.27 and 2.28 and in Photo 2.5. In the first stage of soaking, the salts dissolved into the soaked water and the mass of the specimens decreased. In the following stage, which is identified by the appearance of cracks or fractures in the specimens, the specimens increased in both mass and volume, and the salt concentration of the soaked water rose remarkably. The X-ray diffraction analysis and scanning electronic microscope observations clarified that NaCl and KCl leached from the stabilized ash in the first stage, and consequently, the cement component realized hydration to form some by-products, such as ettringite and calcium-aluminate hydrate (CAH; $CaO \cdot Al_2O_3 \cdot H_2O$). It can be concluded, therefore, that the soaking durability is affected by salt leaching and the hydration of cement components.

2.6 Conclusions

In this chapter, we discussed the stabilization and utilization of fly ash and slag waste materials from the standpoint of environmental geotechnology. Fluidized bed combustion coal fly ash (FCA), stainless-steel slag (S-slag) and municipal solid waste incinerated fly ash (MSW fly ash) were assessed in terms of their stabilization effect and geotechnical application. The main results obtained in this chapter can be summarized as follows:

(1) Due to its lime and gypsum contents, FCA showed remarkable strength development by compaction and aging with or without a hardening agent, and thus, may be utilized for embankments or as a road subbase material. In addition, there is little possibility of a negative environmental impact due to harmful substances within this material.

(2) The use of the "Non-Dusty Method," which adds waste oil, is proposed and evaluated. This method prevents dust effectively, and considering the hardening characteristics under soaking conditions, the material treated by the Non-Dusty Method is applicable to earthen works.

(3) The addition of FCA contributes to the stabilization and/or solidification of a soft ground. From the perspective of soaking or the remolding durability, the soil materials stabilized by FCA with or without Carbonated-Aluminate Salt (CAS) can be employed as earthen

materials for embankments, road bases, and other similar applications.

(4) The field-scale tests showed that general construction concepts and equipment are available for the proposed methods. The construction performance and follow-up examinations clarified that any ground or soil stabilized by FCA with CAS would be improved as well or better than by using only an ordinary cement-based stabilizer.

(5) Two types of S-slag were tested as typical electric reducing slags to establish their potential use as ground materials in view of their physical properties and chemical composition. The main minerals constituting S-slag are merwinite ($Ca_3Mg(SiO_4)_2$), diopside ($CaMg(SiO_3)_2$), magnesium aluminum oxide ($MgO \cdot Al_2O_3$), and magnesium silicate (β-$2MgO \cdot SiO_2$).

(6) The use of Carbonated-Aluminate Salt (CAS) accelerates the formation of hydrated by-products, namely, CSH ($CaO \cdot SiO_2 \cdot H_2O$) and CASH ($CaO \cdot Al_2O_3 \cdot SiO_2 \cdot H_2O$). It is thought that these hydrates contribute to the strength development of S-slag mixtures, and that strength deterioration due to the expansion of S-slags does not occur.

(7) With the addition of kaolinite, the specimens showed an improvement in durability. It has been confirmed that the supplement of fine grain materials to S-slag brings about denser mixtures.

(8) The durability of stabilized S-slag mixtures depends on the properties of the materials and the curing conditions. Drying conditions with a raised temperature can accelerate the hardening reaction of the stabilized S-slags. The Vacuum drying method proposed in this study is effective for assessing the drying-wetting durability of mixtures stabilized by cement because it achieves sufficient dehydration of specimens by keeping the temperature constant and normal.

(9) From the standpoint of strength development and the durability characteristics of stabilized S-slag, it is concluded that S-slag has the potential for use as a subbase course material if it is treated with CAS and kaolinite.

(10) The cement stabilization of the municipal solid waste incinerated fly ash (MSW fly ash) does not have enough of an effect on the strength development and the soaking durability. The addition of cement can only contribute to the containment of heavy metals due to the high level of alkaline.

(11) When using FCA as a stabilizing agent for MSW fly ash, the mixture exhibits high strength and durability, however, the Cd leachate can not be prevented in the early stages of curing.

(12) The multiple use of cement and FCA as a MSW fly ash stabilizer can attain strength development, high soaking durability, and the containment of heavy metals. The method is effective for landfilling with MSW fly ash.

(13) The behavior of soluble salts contained in the MSW fly ash can greatly affect strength

development, the soaking durability, and the hardening reaction of the stabilized MSW fly ash mixtures.

References for Chapter 2

Behr-Andres, C.B. and N.J. Hutzler (1994). "Characterization and use of fluidized bed combustion coal ash," *Jour. Geotech. Engrg.*, ASCE, Vol.120, No.6, pp.1488-1506.

Edil, T.B., L.K. Sandstrom and P.M. Berthouex (1992). "Interaction of inorganic leachate with compacted pozzolanic fly ash," *Jour. Geotech. Engrg.*, ASCE, Vol.118, No.9, pp.1410-1430.

Fujiwara, Y., R. Miyazaki, M. Fukasawa and T. Sueka (1992). "Contaminant adsorption properties of coal ash containing high content of unburned substance and its utilization," *Proc. 37th National Symp. on Soil Mech. and Found. Engrg.*, JSSMFE, pp.25-30 (in Japanese).

Gerdes, A. and F.H. Wittmann (1994). "Use of ashes from MSW incineration in cementitous building materials," *Proc. Environmental Aspects of Construction with Waste Materials*, Elsevier, pp.905-908.

Gidley, J.S. and W.S. Sack (1984). "Environmental aspects of wastes utilization in construction," *Jour. Environ. Engrg.*, ASCE, Vol.110, No.6, pp.1117-1133.

Hartlen, J. (1994). "Use of incinerator bottom ash as filling material," *Proc. 13th Int. Conf. on Soil Mech. and Found. Engrg.*, New Delhi, Vol.4, pp.1583-1586.

Hiraoka, M. and S. Sakai (1994). "The properties of fly ash from municipal waste incineration and its future treatment technologies," *Waste Management Research*, Vol.5, No.1, pp.3-17 (in Japanese).

Horiuchi, S. K. Tamaoki and K. Yasuhara (1995). "Coal ash slurry for effective underwater disposal," *Soils and Foundations*, JSSMFE, Vol.35, No.1, pp.1-10.

Hosoda, N. (1994). "Mechanical characteristics of F.B.C ash," *Proc. 1st National Symp. on Environmental Geotechnology*, pp.183-190, 1994 (in Japanese).

Hudales, J.B.M. (1994). "The use of MWI fly ash in asphalt for road construction," *Proc. Environmental Aspects of Construction with Waste Materials*, Elsevier, pp.227-232.

The Iron and Steel Institute of Japan (1979). "Properties and utilization of iron making and steel making slags," *Iron and Steel*, Vol.65, No.12, pp.1787-1811 (in Japanese).

Janardhanam, R., F. Burns and R.D. Peindl (1992). "Mix design for flowable fly-ash backfill material," *Jour. Mater. Engrg.*, ASCE, Vol.4, No.3, pp.252-263.

Joshi, R.C., Thomas, J.O. and Adam, R.B. (1992). "Properties of gypsum wallboards containing fly ash," *Jour. Mater. Engrg.*, ASCE, Vol.4, No.2, pp.212-225.

Kamon, M. and Katsumi, T. (1994). "Utilization of waste slurry from construction works,"

Proc. 13th Int. Conf. on Soil Mech. and Found. Engrg., New Delhi, Vol.4, pp.1613-1616.

Kamon, M., T. Katsumi and Y. Sano (1994). "Stabilization of municipal waste incineration fly ash," *Proc. 1st National Symp. on Environmental Geotechnology*, pp.231-238, (in Japanese).

Kamon, M. and S. Nontananandh, S. (1990). "Contribution of stainless-steel slag to the development of strength for seabed hedoro," *Soils and Foundations*, JSSMFE, Vol. 30, No. 4, pp. 63-72.

Kamon, M., S. Nontananandh and T. Katsumi (1991). "Utilization of industrial wastes by solidification," *Jour. Soc. Mat. Sci., Japan*, Vol.40, No.459, pp.22-28 (in Japanese).

Kamon, M., S. Nontananandh and T. Katsumi (1993). "Utilization of stainless-steel slag by cement hardening," *Soils and Foundations*, JSSMFE, Vol.33, No.3, pp.118-129.

Kamon, M., K. Sawa and S. Tomohisa (1989). "On stabilization of hedoro by using cement group hardening materials," *Jour. Society of Materials Science, Japan*, Vol.38, No. 432, pp. 1092-1097 (in Japanese).

Kamon, M., K. Sawa and S. Tomohisa (1990). "The utilization of paper ash by the cement group hardening," *Proc. 25th JSSMFE*, Okayama, pp. 1937-1938 (in Japanese).

Kamon, M., S. Tomohisa and S. Nontananandh (1991). "Environmental geotechnology for potential waste utilization," *Proc. 9th Asian Regional Conf. on SMFE*, Bangkok, Vol.1, pp.397-400.

Kawasaki, H., Horiuchi, S., Akatsuka, M. and Sano, S. (1992). "Fly-ash slurry island II. Construction in Hakucho Ohashi Project," *Jour. Mater. Engrg.*, ASCE, Vol.4, No.2, pp.134-152.

Kokado, M. (1994). "Research on the treatment of fly ash from MSWI in Tokyo," *Waste Management Research*, Vol.5, No.1, pp.46-59 (in Japanese).

Kuwayama, T., A. Honda and T. Mise (1988). "Expansion of electric arc furnace slag by water adsorption," *Jour. Society of Materials Science, Japan*, Vol.37, No.422, pp.1278-1283, (in Japanese).

Kuwayama, T., M. Yamada, A. Honda and T. Mise (1990). "Physical and chemical properties of steel making slags produced by electric furnace," *Tsuchi-to-Kiso*, JSSMFE, Vol.38, No.12, pp.23-28, (in Japanese).

Kuwayama, T., T. Mise, M. Yamada and A. Honda (1992). "Engineering properties of electric furnace slags, Soil Improvement," *Current Japanese Materials Research Vol. 9*, JSMS, Elsevier Applied Science, pp. 85-100.

Maher, M.H., J.M. Butziger and Y.S. Chae (1992). "Utilization of municipal solid waste ash as a construction materials," Environmental Geotechnology, Usmen and Acar (eds.), Cesme, Turkey, pp.457-466.

Means, J.L., L.A. Smith, K.W. Nehring, S.E. Brauning, A.R. Gavaskar, B.M. Sass, C.C.

Wiles and C.I. Mashni (1995). *The application of solidification/stabilization to waste materials,* Lewis Publishers, 334p.

Mehta, P.K. (1973). "Mechanism of expansion associated with ettringite formation," *Cement and Concrete Research,* Vol.3, pp.1-6.

Mehta, P.K. (1989). "Pozzolanic and cementituous by-products in concrete - another look," *Proc. 3rd Int. Conf. on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete,* Trondheim, Norway, Vol.1.

Narita, K., T. Onoye and Z. Takata (1978). "On the weathering mechanism of LD Converter Slag," *Iron and Steel,* Vol. 64, No. 10, pp. 68-77 (in Japanese).

Nishi, M., N. Yoshida, S. Kigoshi, H. Ohta and A. Maeda (1994). "Performance evaluation of coal ash treated subgrade in asphalt pavement," *Prediction versus Performance in Geotechnical Engineering*, Balasubramaniam et al. (eds), Balkema, pp.85-94.

Nontananandh, S. (1990). "Industrial waste utilization as construction materials by chemical stabilization," Dr. Eng. dissertation, Kyoto University, 347p.

Ohora, M., T. Teramae and H. Niijima (1990). "Experimental study of fluidized combustion coal ash for subbase course materials," *Proc. 25th JSSMFE,* pp.1801-1802, (in Japanese).

Pandey, K.K., G.A. Canty, A. Atalay, J.M. Robertson and J.G. Laguros (1995). "Fluidized bed ash as a soil stabilizer in highway construction," *Proc. ASCE Specialty Conf. Geoenvironment 2000*, ASCE, New Orleans, pp.1422-1436.

Poran, C.J., and F. Ahtchi-Ali (1989). "Properties of solid waste incinerator fly ash," *Jour. Geotech. Engrg.*, ASCE, Vol.115, No.8, pp.1118-1133.

Rogbeck, J. and P. Elander (1994). "Potentials for utilisation of PFBC ash," *Proc. Environmental Aspects of Construction with Waste Materials*, Elsevier, pp.589-598.

Sawa, K., S. Tomohisa, K. Sasabe, A. Koto and K. Suzuki (1995). "Development of dustless hardening material containing small amount of oil," *Jour. Soc. Mat. Sci., Japan,* Vol.44, No.503, pp.1027-1030 (in Japanese).

Shimaoka, T. and M. Hanashima (1994). "The behavior of fly ash stabilized by cement solidification in landfills," *Waste Management Research,* Vol.5, No.1, pp.32-45 (in Japanese).

Shinano, T. (1991). "Utilization of Fluidized-Bed Combustion Ash," *Preprint, 23rd Conference of International Energy Agency and Atmospheric Fluidized Bed Combustion,* Florence.

Steel Slag Association, Japan (1985). *Manual for design and construction of steel slag roadbase,* 81p (in Japanese).

Tanaka, M., M. Osako, H. Kawamoto and H. Inagawa (1992). "Leachate of heavy metals from the MSW fly ash in landfill and its prevention," *Proc. 13th Environmental and Sanitary Engineering Research, Kyoto University,* pp.258-229.

Tomizawa, S., K. Kamiya, M. Kawamura and S. Toyama (1979). "Chemical composition and leachate components of the MSW incinerated fly ash from electrostatic precipitator," *Jour. Chemical Soc. Japan*, No.7, pp.946-950.

Tomohisa, S. (1989). "Stabilization of problem soils and industrial wastes by cement or lime hardening and estimate method of strength development," Dr. Eng. dissertation, Kyoto University, 284p (in Japanese).

Toth, P.S., H.T. Chan and C.B. Cragg (1988). "Coal ash as structural fill, with special reference to Ontario experience," *Can. Geotech. Jour.*, Vol.25, pp.694-704.

Triano, J.R. and G.C. Frantz (1992). "Durability of MSW fly-ash concrete," *Jour. Mater. Civil Engrg.*, ASCE, Vol.4, No.4, pp.369-384.

Wright III, L.M. and C.D. Shackelford (1995). "Compatibility of soil admixed fly ash to acetic acid," *Proc. ASCE Specialty Conf. Geoenvironment 2000*, ASCE, pp.196-212.

CHAPTER 3

Stabilization and Utilization of Sludge Materials

3.1 General Remarks

Many kinds of sludge and slurry are discharged in large quantities from various industries, including construction works, and are regarded as waste under the Japanese legal system on waste management. The amount of sludge generation per year adds up to more than 160,000 Gg, which is about 40% of the total waste being discharged. Only about 7% and 18% were recycled and reduced, respectively, in 1990 in Japan (Environmental Agency, Japan 1995). The treatment of sludge from construction works is one of the most important concerns in terms of both geotechnical and environmental viewpoints. Waste sludge and slurry discharged from construction works are generated at a rate of 15,000 Gg per year, and unfortunately, recycling and treatment (reduction) ratios are very low, 2% and 6%, respectively (Ministry of Construction 1995). Most of the slurry from construction works is merely disposed of, therefore, and some of it is even illegally dumped. Consequently, a great potential for causing geo-environmental and social problems exists. In addition, large quantities of sediment are dredged annually from the bottom of harbors, lakes, and rivers in order to purify the water or to maintain a navigable waterway. As the generation of such sludge close to the construction industry is so immense, the treatment and disposal of it are important tasks for the prevention of direct or indirect negative impacts on the environment and on society in general.

The sludge is basically a mixture of hazardous or nonhazardous solid particles and water (or liquid). Most of it consists of a large amount of water in which a small quantity of solids exists, and consequently, it exhibits a high water content of 100-1000%. Some sludge raises environmental concern during and after treatment. Dredged sludge sometimes exhibits toxicity due to the hazardous chemicals which originate from the wastewater which is discharged from industrial and domestic activities. In some construction slurries, organic compounds remain which can lead to organic pollution and cause high values of COD (chemical oxygen demand) or BOD (biochemical oxygen demand).

Geotechnical considerations have been addressed in sludge management. The engineering behavior of sludge and slurry in sediment or mine tailings have been an important issue in environmental geotechnology in recent decades (e.g., Kamon 1978; Zyl 1993; Rollings 1994; Morgenstern 1995). In particular, the solidification of seabed sludge has been researched using ground improvement techniques in view of soil stabilization (Kamon et al. 1989; JSMS 1991; JCA 1994; Ogino et al. 1994). Some researchers emphasized that these techniques can be applied for the containment of hazardous substances as well as for solidification (Tashiro et al. 1979; Kujala 1989). Dehydration methods and equipment have also been developed for economical treatment, especially for the waste slurry discharged from foundation works (Kita and Tsuji 1981; Naemura and Ogawa 1992). As landfill sites in which the sludge can be disposed of are limited at present, concepts and methods for sludge utilization should be established for synthetic purposes, environment preservation, resource use, and social requirements beyond these technical experiences.

In this chapter, the treatment of the sludge close to construction works will be discussed for utilization purposes. The present state of the proposed regulatory requirements and treatment methods will be summarized in the Section 3.2. The cement stabilization method will be evaluated through the assessment of a strength development mechanism, durability, and environmental impact in Section 3.3, because the stabilization method must be applicable to the treatment of sludge with a remarkably high water content. In Section 3.4, we will propose a treatment system for slurry from construction works which consists of two methods, dehydration and solidification, in order to attain an efficient treatment, a decrease in volume, stabilization, and recycling.

3.2 Background

3.2.1 Sludge Generation and Governmental Regulations

Waste sludge/slurry and waste turbid water are generated from foundation works in large quantities. They cannot be released into rivers or seas, nor can they be reclaimed for embankments as earthen materials. Waste slurry is a by-product of the slurry which is used in the construction of cast-in-place concrete piles, continuous diaphragm walls, shield tunnels, and other similar structures. Turbid water is discharged from tunnels or collected around new land development areas by means of excavating, cutting and filling embankments. The engineering and environmental properties of waste slurry are strongly affected by their origins and the applied methods, and are summarized in Table 3.1 (Kawachi et al. 1996).

Waste slurry and turbid water should be treated by a proper intermediate method; then the treated water can be released into rivers or sewage systems according to the environmental criteria in Table 3.2. Of the criteria, the observance of SS (suspended solids), pH (potential of

Table 3.1 Properties of waste slurry from construction works

Origin	Composition	Solid content
Excavation of soft ground	Soil (Clay, Silt)	above 50%
Slurry excavation method		
Diaphragm wall or piling	Bentonite, Polymer, Dispersant, Soil ...	5-40%
Shield tunneling	Bentonite, Soil (Clay), Foaming agent ...	5-50%
Ground improvement (SMW, DMM, Grouting)	Cement, Bentonite, Soil ... (able to harden)	25-50%
Dredging	Soil, Organic matter	10-30%

Table 3.2 Effluent standard settled by law

	Water Pollution Control Law	Sewage Law	Environmental quality standard	
			Rivers & Lakes	Sea
SS (mg/l)	200	600	below 1 - below 25	-
pH	5 (5.8) - 9 (8.6)	5 - 9	6.5 (6.0) - 8.5	7.8 (7.0) - 8.3
BOD (mg/l)	160 (120)	600	below 1 - below 10	-
COD (mg/l)	160 (120)	-	below 1 - below 8	below 2 - below 8
Mineral oil (mg/l)	5	5	-	-
Animal oil (mg/l)	30	30	-	-

hydrogen), COD (chemical oxygen demands), and the oil content are important concerns in terms of the treatment of these wastes. Soils and dehydrated cakes are also produced by an intermediate treatment. Only the soils fulfilling the criteria set down by the Ministry of Construction (q_c = 2 kgf/cm^2 (196 kPa) or q_u = 0.5 kgf/cm^2 (49 kPa)), which classifies surplus soil and waste slurry, can be utilized as earthen materials for embankments, backfill, and other similar applications, while soils and cakes which are lower quality should only be disposed of at landfill sites and not be reused. In order that construction machinery and trucks can track on the stabilized sludge, it should have a compressive strength of 50-100 kPa. There are some cases, however, in which an increase in strength over a long period of time is not required. If the stabilized sludge is placed in a shallow part of the ground, it has the potential to be excavated in the future in order to re-construct the facilities, and thus it should not be stabilized too hard or strongly.

3.2.2 Treatment Method

As sludge/slurry and waste water contain a large amount of water, dehydration is thought to be an important and effective method of volume reduction. Figure 3.1 shows the ordinary flow of waste sludge treatment. Certain steps can be omitted and some must be added according to the

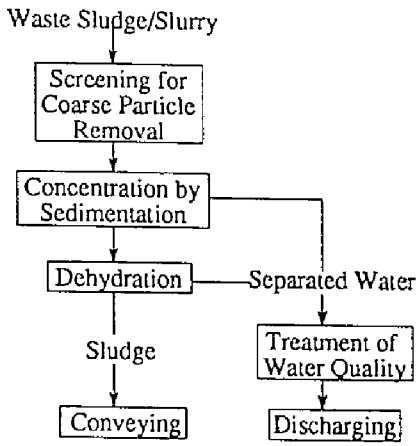


Fig. 3.1 Ordinary flow of waste sludge/slurry management

Table 3.3 Dehydration plants and engineering properties of dehydrated cakes

Dehydrator		Dehydrated cake	
Type of dehydrator	Working pressure	Water content (%)	Cone index (kPa)
Filter-press (ordinary)	500 - 700 kPa	(0.8 - 0.9) x w_L	100 - 1000
Filter-press (high-pressure)	4000 kPa	(0.6 - 0.8) x w_L	1000 - 3000
Belt-press	100 - 150 kPa	1.0 x w_L	0 - 200
Screw decanter	500 - 2000 G	(1.0 - 1.2) x w_L	0

w_L : Liquid limit (%), G : Acceleration of gravity (9.8 m/s^2)

characteristics of the waste slurry, the environmental criteria to be reached, and the geotechnical applicability of the dehydrated soil and environmental compatibility of the treated water. Although the most important process is dehydration, sludge is difficult to dehydrate rapidly since it contains many fine particles. For slurry excavation methods in which bentonite or polymers such as carboxyl-methyl cellulose (CMC) are often used to regulate the viscosity, these dispersants remain in the waste slurry and make it very difficult to dehydrate. In order to solve this problem, certain kinds of flocclulant chemicals and dehydration plants have been developed and utilized. Inorganic materials such as $Al_2(SO_4)_3$ and PAC (polyaluminium chloride) and polymers such as polyaclylamide are usually used as flocculating agents. Table 3.3 shows the dehydration plants which have been developed. Use of the Filter-press method and the Roller-press method is becoming widespread.

Many attempts have been made recently to utilize sludge. Treatment techniques and their applications are summarized in Fig. 3.2 (Kawachi et al. 1996). The newly-developed special techniques can be divided into three broad categories. The first group is comprised of the techniques which realize the value added based on traditional soil stabilization methods. Representatives of this are the "Liquefied soil stabilization method" in which fresh cement-soil mixtures are slurried for backfilling, the "Light weight soil stabilization method" in which EPS

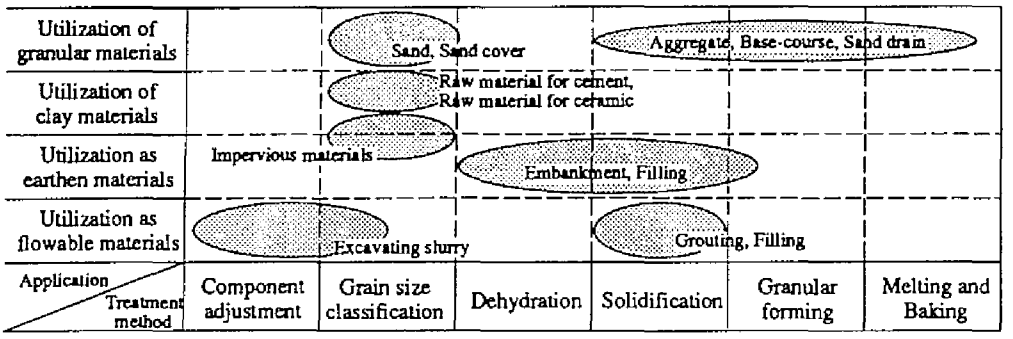


Fig. 3.2 Concept of relationship between treatment method and application of construction waste sludge/slurry

(expanded poly-styrene) and/or air bubbles with cement are used, and the "Geotextile tube dehydration method" in which sludge is poured into a fabric tube to be dehydrated (Miki et al. 1992 and 1994). The second group of technique contains advanced technological methods, such as "melting" or "baking", in which the high cost and energy are invested. Slag and bricks are produced with these methods and are satisfactorily utilized as construction materials due to their excellent engineering properties (Kawachi et al. 1994; Tanaka et al. 1994; Kajihara and Kusumi 1994). The last group of techniques focuses on the basic properties and chemical composition of sludge and realizes its utilization as a raw material. Tay and Show (1990) and Kamon and Nontananandh (1991) proposed methods wherein the cement can be made from the sludge from industrial works by baking.

Solidification and dehydration maintain major positions in Fig. 3.2. Recently, researchers have tried to apply these methods not only for the treatment of waste slurry, but also for recycling as earthen materials, such as embankment (e.g., Ogino et al. 1994). As the soil to be solidified exhibits such a high water content, the hardening mechanisms and the durability are important concerns in order for the methods to be widely distributed. Volume reduction is another big point, and therefore, solidification and dehydration must be properly executed for an effective treatment. Environmental concern should be felt during the assessment of sludge utilization.

3.3 Solidification of Waste Sludge

3.3.1 Hardening Effect of Cement Stabilized Sludge

(1) Experimental procedure

The investigation of hardening effects and mechanisms is one of the most important concerns in sludge solidification, as stated in Sections 3.1 and 3.2. A series of the experimental studies was conducted on sludge dredged from a river bottom. The sludge was sampled from the sediment

Table 3.4 Physical properties of sludge used

Natural water content (%)	430.3
Wet density (g/cm^3)	1.105
Particle density (g/cm^3)	2.324
Consistency	
Liquid limit (%)	215.5
Plastic limit (%)	76.2
Plasticity index (%)	139.3
Grain size distribution (%)	
Sand fraction (%)	1.6
Silt fraction (%)	62.4
Clay fraction (%)	36.4
Ignition loss (%)	24.1

Table 3.5 Chemical composition of sludge used

pH	8.1
Chemical composition (%)	
SiO_2 (%)	67.7
Al_2O_3 (%)	26.1
Fe_2O_3 (%)	4.8
CaO (%)	1.4
Pb (mg/kg)	216
Cr(VI) (mg/kg)	< 2
As (mg/kg)	13.4
S (mg/kg)	2930
N (NH_3) (mg/kg)	905
Leachate composition	
Pb (mg/l)	< 0.02
Cr(VI) (mg/l)	< 0.04
As (mg/l)	< 0.005
Gas content	
H_2S (mg/kg)	2240
NH_3 (mg/kg)	727
Extraction of n-hexane (mg/kg)	3970

Table 3.6 Mixtures and chemical composition of stabilizers used

	Mixing proportion (%)				Chemical composition (%)				
Type	Cement	Gypsum	PBFSC	S-slag	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3
HC	100	-	-	-	63.8	22.1	5.0	3.0	2.0
HCS	95	-	-	5	62.1	22.0	5.3	3.2	1.9
HCG	90	10	-	-	61.3	19.9	4.5	2.7	7.3
HCL	50	-	50	-	59.3	24.1	6.7	2.6	2.0

PBFSC: Portland blast-furnace slag cement (B-type)

layer, 0-2 m in depth in a river bottom in Osaka City. The physical properties and chemical composition are presented in Tables 3.4 and 3.5, respectively. The natural water content was very high (higher than 400%), but the particles did not sediment and the sludge maintained a slurry condition. The suspension phenomenon may be due to the high composition of organic components which is indicated by the high value (24%) of ignition loss ratio. These organic components behave as a hydrophilic colloid; they can adsorb and cover the surface of soil particles, and consequently, prevent the particles from flocculating.

The stabilizing agents used in the test studies are the materials shown in Table 3.6. In the case of the stabilization of soft soil with a high water content, a specially blended stabilizer with cement, gypsum, and slag is used. In particular, a mixture of gypsum and cement can be effective in promoting the formation of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$), one of the hydrated by-products (Kutara et al. 1984). Some researchers have emphasized that waste materials, such as stainless-steel slag, can be effectively applied to sludge stabilization (Kamon and Supakij 1990).

The specimens were prepared for the unconfined compressive strength tests in accordance with the Practice for Making and Curing Noncompacted Stabilized Soil Specimens (JGS T 511-1990). An X-ray diffraction (XRD) analysis and scanning electron microscope (SEM) observations were performed on some samples whose strength tests were completed in order to assess the mechanisms of the hardening reaction.

(2) Strength development

Strength developments are shown in Fig. 3.3. Strength development characteristics are strongly affected by the type of stabilizer used. The applicability of stabilized sludge to a shallow part of the ground, such as a subgrade or embankment, is recommended from the range of developed strength. It can be judged from the strength development characteristics. The stabilized sludge should have a strength higher than 50 kPa at an early stage (1 day or 7 days) in order to be regarded as soil and not as waste, should reach about 100 kPa in 7 days in order to be utilized as a subgrade or embankment, and should maintain a strength lower than 300 kPa over a long period (28 or 90 days) because it may be excavated again in a future re-construction.

When using HC (only cement), the addition of 180 kg/m^3 of HC brought about a higher 7-day strength than 50 kPa to be regarded as soil. The sludge stabilized by 240 kg/cm^3 of HC is applicable to subgrade as it reaches 100 kPa, however, it is not suitable for subgrade because of its remarkably high strength over a longer period. The addition of HCS has a similar tendency as that for HC. Since the sludge stabilized by HCL exhibits the highest strength development, especially over a longer curing period, the application of HCL stabilized sludge for various purposes can be considered. It is not recommended, however, for use as an earthen material for a shallow ground due to its remarkably high strength over a long curing term. In terms of its applicability to subgrade or embankments, HCG can be the most suitable stabilizer for sludge because it can develop high strength at an early age, but does not develop a much higher

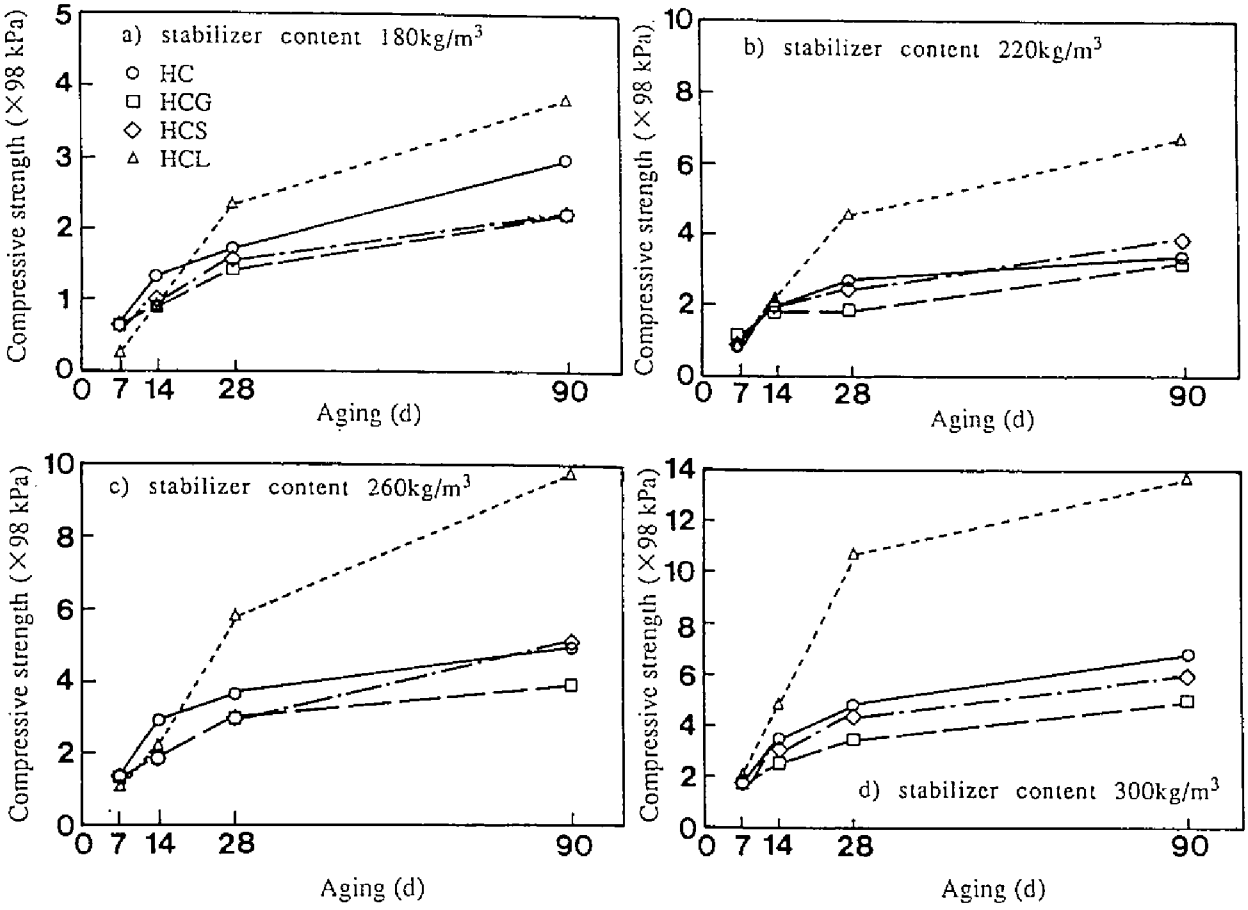


Fig. 3.3 Strength development of stabilized sludge

strength over a longer curing period. The sludge stabilized by HCG can be applied to embankments or subgrade with a wide range of additive content, such as 220-260 kg/m^3, if the criteria is set as a higher 7-day strength than 100 kPa and a lower 28-day strength than 300 kPa.

(3) Hardening mechanism

From the XRD patterns of the stabilized sludge, shown in Fig. 3.4, calcium aluminate carbonated hydrate ($7CaO \cdot 2Al_2O_3 \cdot CaCO_3 \cdot 24H_2O$) and ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) were the main compounds detected.

The formation of ettringite is believed to have a stabilizing effect on soft ground or sludge and other materials, although it negatively affects concrete due to the expansion phenomenon. Ettringite contributes to the stabilization of soft clay because it forms with a large amount of water, consists of 46% H_2O, as shown in Table 3.7, and consequently, decreases the liquid phase. It is also believed that the formation of ettringite is not greatly affected by the organic matters contained in hedoro. From Fig. 3.5, the development of strength correlates to the XRD intensity of ettringite only in using HCG as a stabilizer, while the sludge stabilized by the other stabilizers (HC, HCS, and HCL) does not show any correlation between the XRD intensity of ettringite and the development of strength. As the sludge used in this study a remarkably high

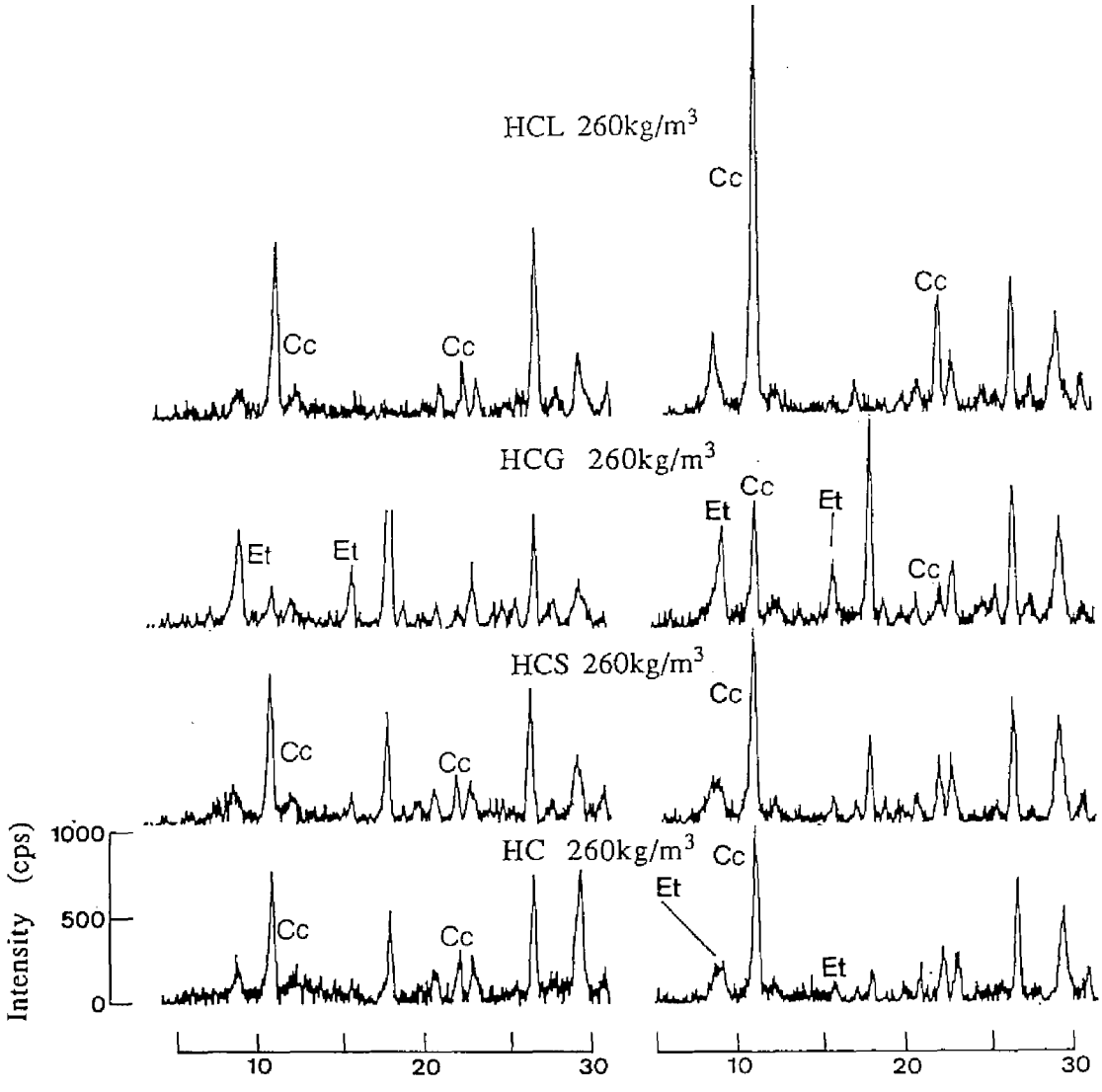


Fig. 3.4 XRD patterns for stabilized sludge

Table 3.7 Composition of chemical compounds in reaction products

Reaction products	Chemical composition (%)				
	CaO	$CaSO_4$	$CaCO_3$	Al_2O_3	H_2O
ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$)	13.3	32.4	-	8.6	45.7
calcium aluminate carbonated hydrate ($7CaO \cdot 2Al_2O_3 \cdot CaCO_3 \cdot 24H_2O$)	34.4	-	8.8	18.9	37.9

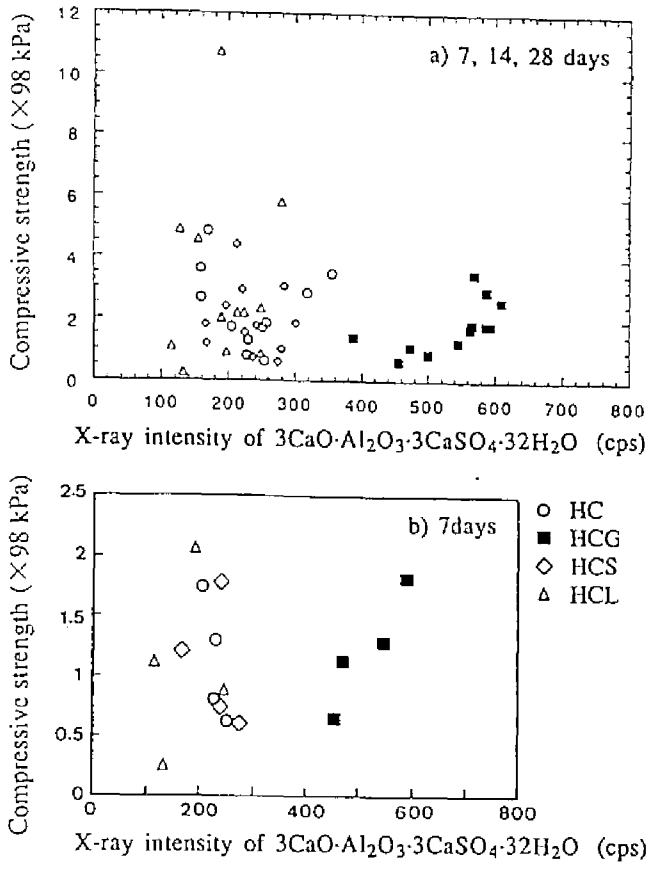


Fig. 3.5 XRD intensity of ettringite and compressive strength

water content, it may be one of the most important effects to contain water during hardening in order to stabilize it. The other by-products or reaction mechanisms must therefore be noticed with regard to water containment.

Figure 3.6 shows the relationship between the XRD intensity of calcium aluminate carbonated hydrate and the gained strength. In contrast to the relationship between ettringite and the compressive strength, shown in Fig. 3.5, there is a strong correlation between the calcium aluminate carbonated hydrate and the strength development when the three stabilizers, HC, HCS, and HCL, were used, which is independent of the types of stabilizers. The strength development has no correlation to this hydrated by-product as to HCG. It can be concluded therefore, that not only does the ettringite contribute to the strength development of sludge with a high water content, but also calcium aluminate carbonated hydrate.

Calcium aluminate carbonated hydrate is a hydrated by-product which has recently been detected through XRD analyses. Except for its detection in lime-stabilized soil, which was cured for a long time (Shimoda et al. 1991), research has been insufficient on this reactive compound. The reason why this rare by-product was used is due to the remarkably high water content of the sludge. The formation of calcium aluminate carbonated hydrate requires a large amount of $CaCO_3$, as shown in Table 3.7. Sludge containing of large amounts of water which is thought

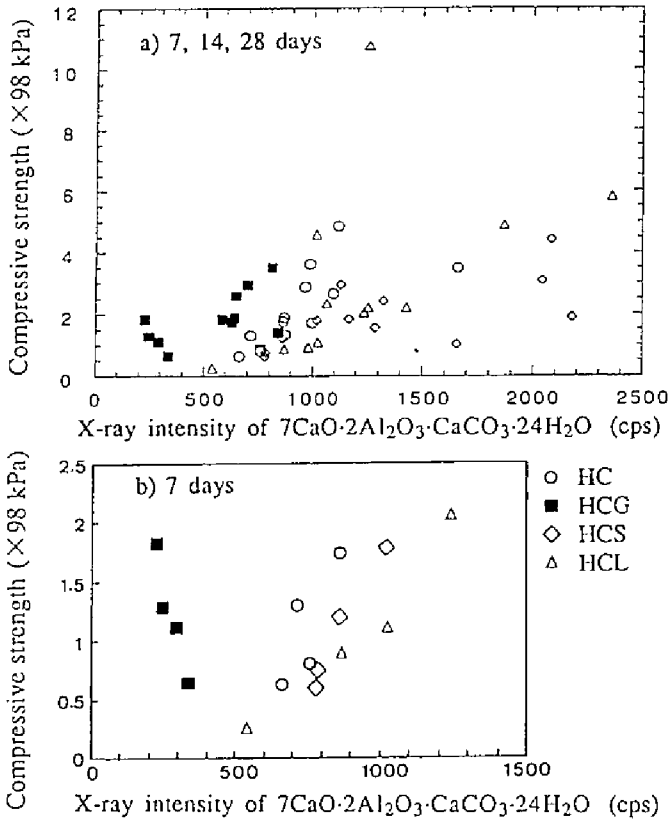
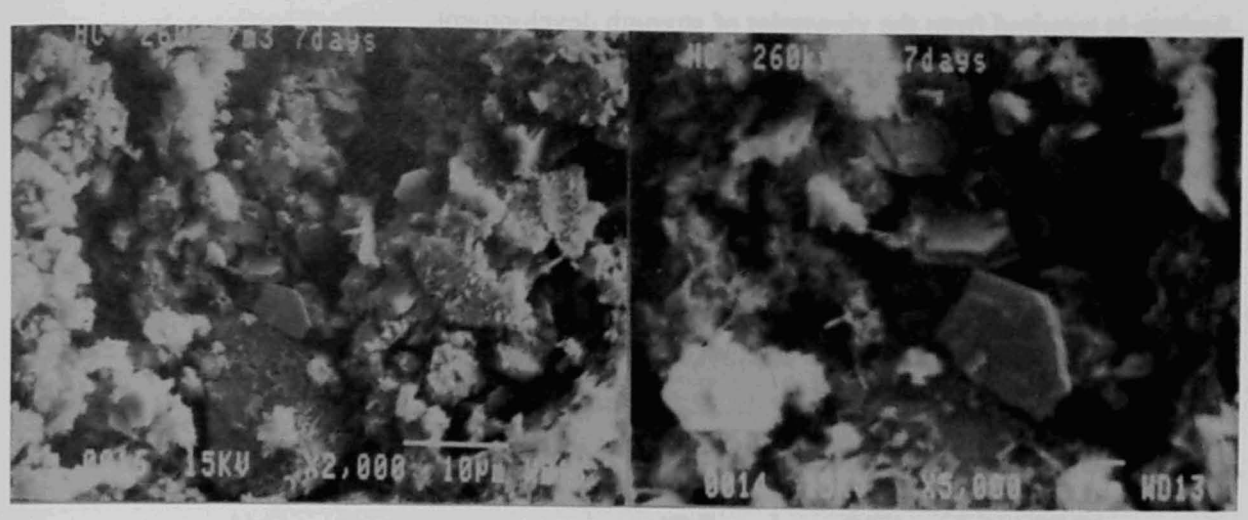


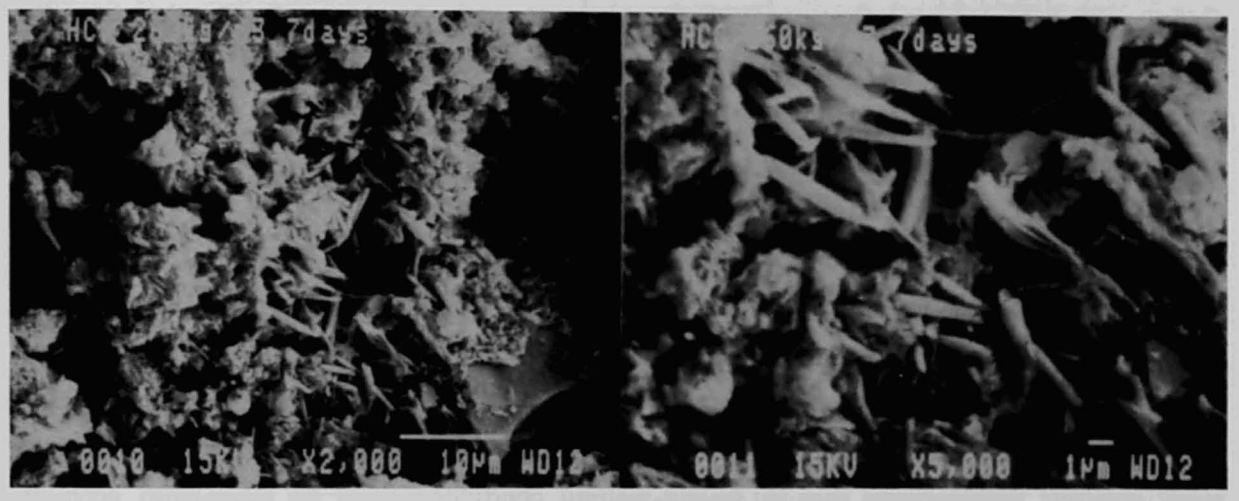
Fig. 3.6 XRD intensity of calcium aluminate carbonated hydrate and compressive strength

to include dissolved CO_2. As a result, the dissolved CO_2 contributes to the formation of calcium aluminate carbonated hydrate, and consequently, to the development of strength.

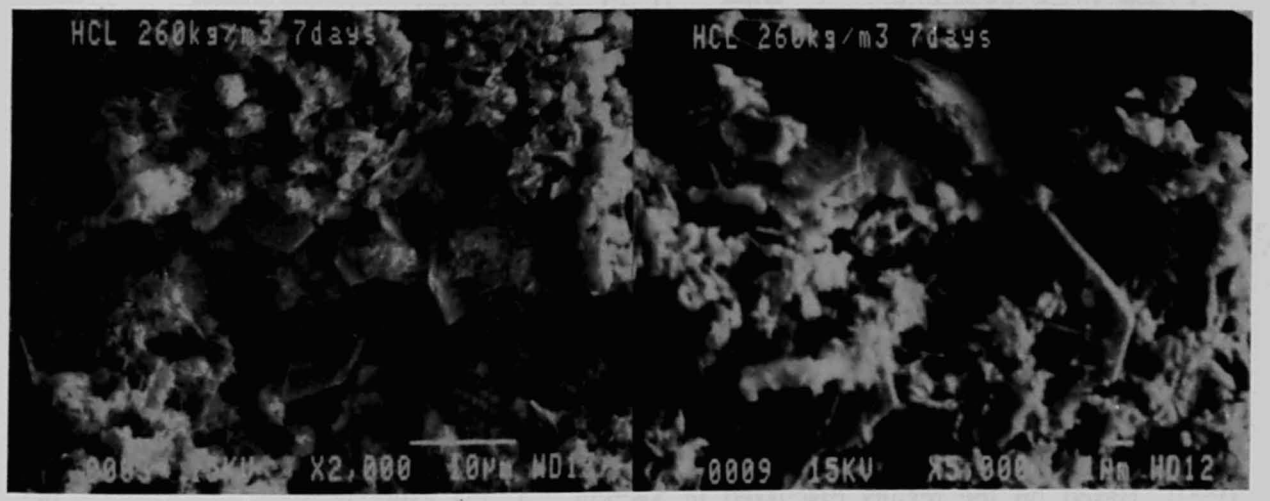
The reason why such compounds as calcium aluminate carbonated hydrate and ettringite are generated during sludge solidification should be addressed. The generation of these compounds can be clearly affected by the type of stabilizer used. From the composition of chemical compounds shown in Table 3.7, the formation of calcium aluminate carbonated hydrate needs larger amounts of alumina than the formation of ettringite. HCL has the highest content of Al_2O_3, as shown in Table 3.6, and therefore, the formation of calcium aluminate carbonated hydrate is thought to be remarkable, and the highest strength was developed. With regard to HCG, Al_2O_3 is consumed to form ettringite because of the existence of gypsum as a component, and consequently, calcium aluminate carbonated hydrate does not form. One of the distinctive characteristics of calcium aluminate carbonated hydrate is its relation to the curing period; sludge stabilized by HCL continues to develop strength over a long curing time, although a remarkable increase in strength over a long period of time was not detected from sludge by HC and HCS. As control of the strength development is very important in terms of design and application, further research on the formation of calcium aluminate carbonated



(a) HC 260 kg/m^3



(b) HCG 260 kg/m^3



(c) HCL 260 kg/m^3

Photo 3.1 SEM micrographs of stabilized sludge at 7 days

hydrate is required from the viewpoint of strength development.

Photo 3.1 shows the SEM photos of the stabilized sludge. The crystals of ettringite have a needle-like shape, 0.0005 mm in diameter and 0.01 mm in length They were detected from sludge stabilized by HCG, which is considered to contribute to the strength development. The ettringite crystals intertwine with each other and the voids between the soil particles are filled. With respect to HC and HCS, the needle-shaped ettringite was also detected, which was not remarkable. Instead of ettringite, a hexagonal plate was mainly detected between the soil particles, and was identified as calcium aluminate carbonated hydrate through an element analysis with an X-ray micro analyzer. It is thought that the formation of calcium aluminate carbonated hydrate contributes to the filling in of pore volume and the strength development.

In conclusion, ettringite and calcium aluminate carbonated hydrate contribute to the development of strength by means of water containment, with regard to the stabilization of sludge with a high water content. With respect to strength development characteristics, the existence of alumina and gypsum affects the formation of these by-products and the strength development characteristics related to the curing age. If a remarkable increase in strength over a longer curing age is not desired, the use of gypsum can be effective because existing alumina will be consumed for the formation of ettringite at an early stage.

3.3.2 Durability of Cement Stabilized Sludge

(1) Experimental procedure

If the solidified sludge is not dumped but reused as an earthen material in construction works, a durability assessment may become an important concern. Particularly, as the sludge whose stabilization is addressed in this chapter has a remarkably high water content, the influence of water removal and seepage due to drying-wetting conditions must be taken into account. Stabilized sludge will be subjected to drying and wetting cycles. Therefore, durability tests against drying-wetting cycles were performed on the sludge stabilized by hardening agents.

Three types of soils were used in this study whose properties are shown in Table 3.8. They all have similar chemical and mineral compositions as they originated from the same general vicinity in Lake Biwa. Their consistency characteristics such as the liquid and the plastic limits, however, were different due to the sediment environment in the lake and the storage conditions in the laboratory. The hardening agents used are shown in Table 3.9. They are cement, a cement and FCA mixture (fluidized bed combustion coal fly ash, discussed in Chapter 2), and a mixture of cement, FCA, and sodium carbonate. The chemical composition of the FCA used here is shown in Table 3.10. The specimens were also prepared in accordance with the Practice for Making and Curing Noncompacted Stabilized Soil Specimens (JGS T 511-1990). Based on the results discussed in Section 2.4, the samples were cured under the following conditions, as shown in Table 3.11.

(1) The samples were sealed and cured at a constant room temperature of 20℃ with 80% relative humidity, called *"Normal curing"*.

Table 3.8 Physical properties and chemical composition of clay soil used

	Clay A	Clay B	Clay C
Particle density (g/cm^3)	2.64	2.63	2.62
Consistency			
Liquid limit (%)	107.0	84.9	77.0
Plastic limit (%)	44.0	34.5	36.6
Plasticity index (%)	63.0	50.4	40.4
Grain size distribution			
Sand fraction (%)	3.0	8.9	8.5
Silt fraction (%)	54.8	51.2	49.0
Clay fraction (%)	42.2	39.9	42.5
Ignition loss (%)	8.3	6.5	6.7
Chemical compositions (%)			
SiO_2	68.2	68.7	69.2
Al_2O_3	28.7	26.4	25.0
CaO	0.5	0.6	0.6
Fe_2O_3	2.0	2.4	2.3

Table 3.9 Mixing proportions of the stabilizers used

	Mixing proportion (%)		
Symbol	Cement	FCA	Na_2CO_3
Cement	100.0	-	-
Stabilizer I	75.0	25.0	-
Stabilizer II	67.5	25.0	7.5

Table 3.10 Physical properties and chemical composition of FCA

Particle density (g/cm^3)	2.28
Blaine specific surface area (cm^2/g)	2868
Ignition loss (%)	39.2
Chemical composition (%)	
SiO_2	23.8
Al_2O_3	16.5
CaO	10.8
Fe_2O_3	3.1
SO_3	1.8
C	36.1
Leachate components (mg/l)	
T-Hg	< 0.0005
Cd	< 0.01
Pb	0.02
Org-P	< 0.01
Cr (VI)	0.04
As	< 0.001
CN^-	< 0.01

1) Leachate components were measured by the leachate test set down by the notification of the Environmental Agency, Japan.

Table 3.11 Experimental conditions for drying-wetting test

Items	Curing conditions	
	Drying	Wetting
(1) Normal curing	sealed, 20±2℃, 80 % RH	
(2) Drying(40℃)-wetting	electric furnace, 40±3℃ 48 hours/cycle	water, 20℃ 24 hours/cycle
(3) Drying(vacuum)-wetting	vacuum vessel, 20±2℃ 48 hours/cycle	water, 20℃ 24 hours/cycle

(2) After being cured and soaked for 6 days and 1 day, respectively, the samples were dried in an electric furnace at 40℃ for a 48-hour cycle and stored in water for a 24-hour cycle, called *"Drying(40℃)-wetting"*.

(3) After being cured and soaked for 6 days and 1 day, respectively, the samples were dried in vacuum desiccators at 20℃ for a 48-hour cycle and stored in water for a 24-hour cycle, called *"Drying(vacuum)-wetting"*;

After being cured under the above conditions, unconfined compressive strength tests and an XRD analysis were conducted.

(2) Influence of drying-wetting on the stabilized sludge

Figures 3.7, 3.8, and 3.9 show changes in weight and volume, compressive strength, and deformation modulus, respectively, under repeated cycles of drying and wetting. As judged from Fig. 3.7, the vacuum desiccator can work as well as thermal drying at 40℃ in terms of water removal by drying, which was also discussed in Section 2.4. The compressive strengths of the samples after each drying step were twice as high as those of the normally cured samples

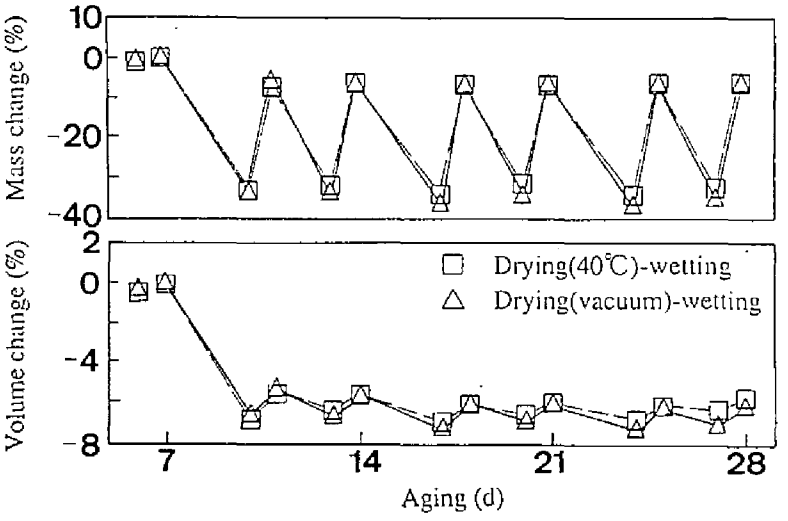


Fig. 3.7 Mass and volume change of stabilized soil under drying-wetting

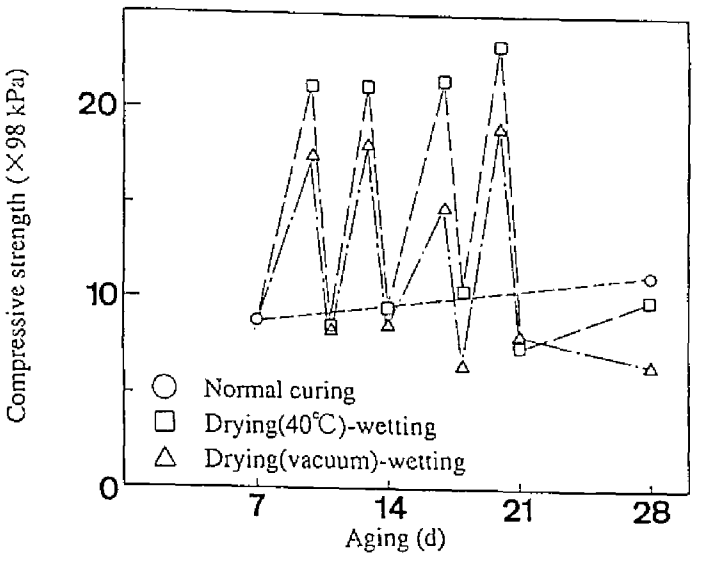


Fig. 3.8 Strength change of stabilized soil subjected to drying-wetting

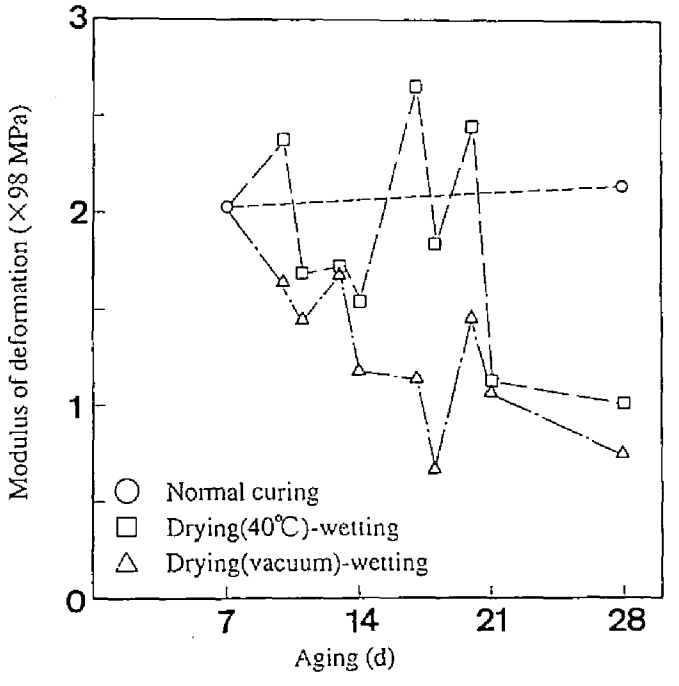


Fig. 3.9 Change in modulus of deformation of stabilized soil subjected to drying-wetting

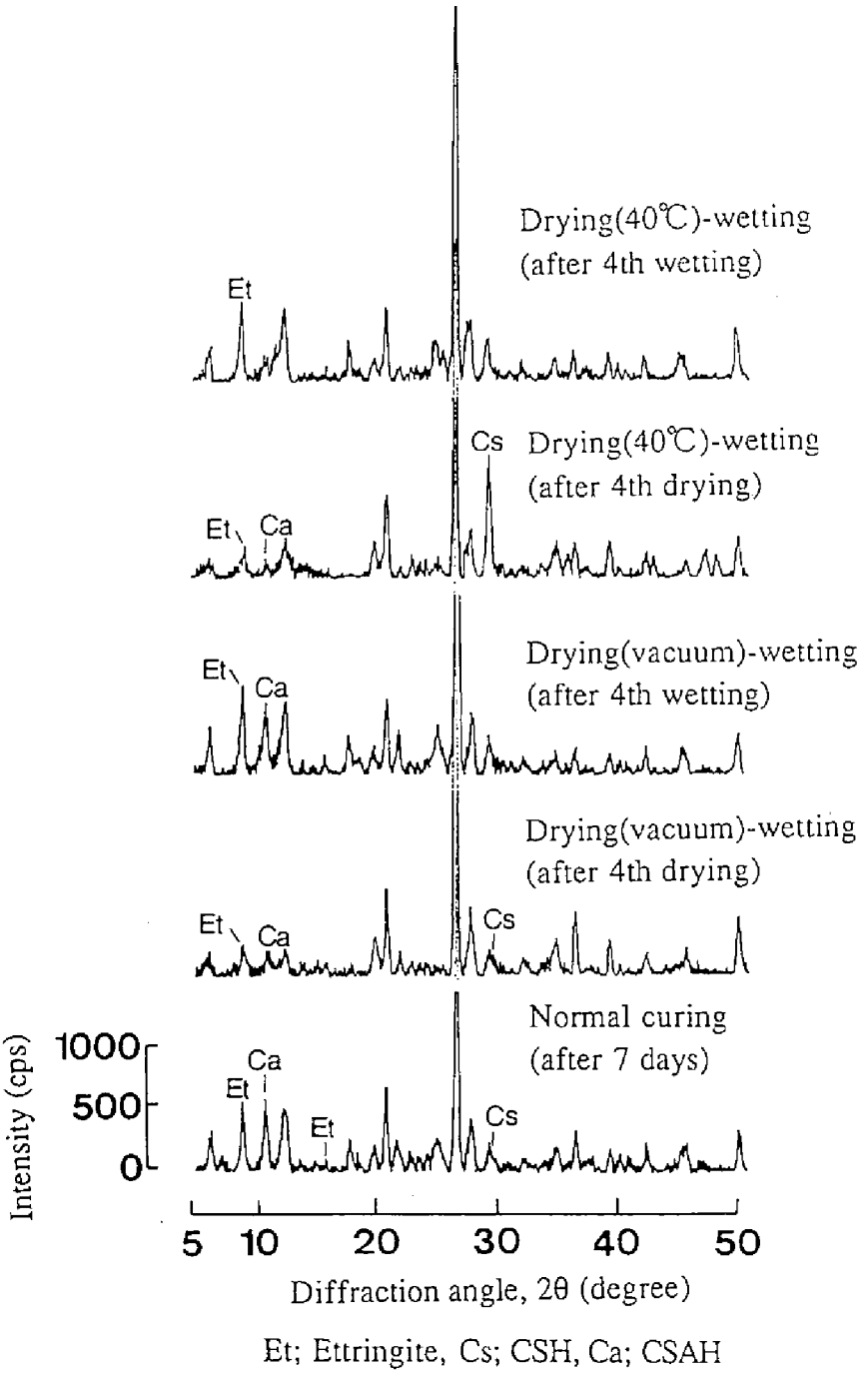


Fig. 3.10 XRD patterns for stabilized soils subjected to drying-wetting

due to shrinkage. The strengths by "40℃ drying" and "vacuum drying" were higher than 2 MPa and 1.5 MPa, respectively, while strengths of the normally cured samples were only about 1 MPa. As the difference in shrinkage between "40℃ drying" and "vacuum drying" was not detected from Fig. 3.7, it is thought that heating accelerates the hardening reaction and contributes to the strength development in the case of "40℃ drying." As a result, even after each wetting step under *"Drying(40℃)-wetting"* the strengths were higher than those under *"Drying(vacuum)-wetting."* This means that since the durability can be overestimated when the thermal drying method is applied, the drying method which uses a vacuum desiccator was clarified to be more effective for the drying-wetting durability assessment.

Repeated cycles of drying and wetting negatively affected the modulus of deformation more than the compressive strength in Fig. 3.9. The samples subjected to drying and wetting cycles grew brittle due to the formation of very fine cracks, which is believed to influence the deformation modulus rather than the decrease in strength.

From the XRD patterns of the stabilized sludge shown in Fig. 3.10, CSH (calcium silicate hydrate; $CaO \cdot SiO_2 \cdot H_2O$), CASH (hydrated gehlenite; $CaO \cdot Al_2O_3 \cdot SiO_2 \cdot H_2O$), and ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) were detected as the main hardening reactive products, and were influenced by the drying-wetting cycles. Ettringite was the most seriously affected reactive products. It disappeared due to the drying steps and recovered after the watering steps. Similar phenomena were also reported by Takano and Sakamaki (1984). With regard to CASH, it disappeared during the drying steps in *Drying(vacuum)-wetting* and was not fully recovered in the wetting process, but it was not affected by the *Drying(vacuum)-wetting* cycles. The production of CSH, which is considered to contribute strongly to the strength development, rose only during the drying step at 40℃. Therefore, the drying method using a vacuum desiccator is effective because it has less influence on the hardening reaction.

(3) Drying-wetting durability of the stabilized sludge

Figure 3.11 shows the changes in strength of the sludge samples subjected to drying-wetting cycles. The initial water content of the 3 soils was adjusted to 92%, 85%, and 80%, respectively, so that a 15% addition of cement may lead to a developed strength of 700-1000 MPa. An acceleration of the hardening reaction due to heat drying in *Drying(40℃)-wetting* was also clearly observed, as the subjected samples have 300-500 kPa higher strengths than the samples subjected to *Drying(vacuum)-wetting*. Even the samples which had a 7-day strength above 900 kPa were stronger than the normally cured samples. Samples with a 7-day strength above 900 kPa did not deteriorate remarkably in strength under the *Drying(vacuum)-wetting* condition. With regard to Soils B and C with a 15% cement addition, which had similar 7-day strengths, stabilized Clay C subjected to *Drying(vacuum)-wetting* had a higher strength in comparison with the *Normal curing* condition after 28 days, while the hardened Clay B subjected to *Drying(vacuum)-wetting* deteriorated in strength compared with the samples cured normally for 28 days. In conclusion, the order of the drying-wetting durability is Soil C, Soil B,

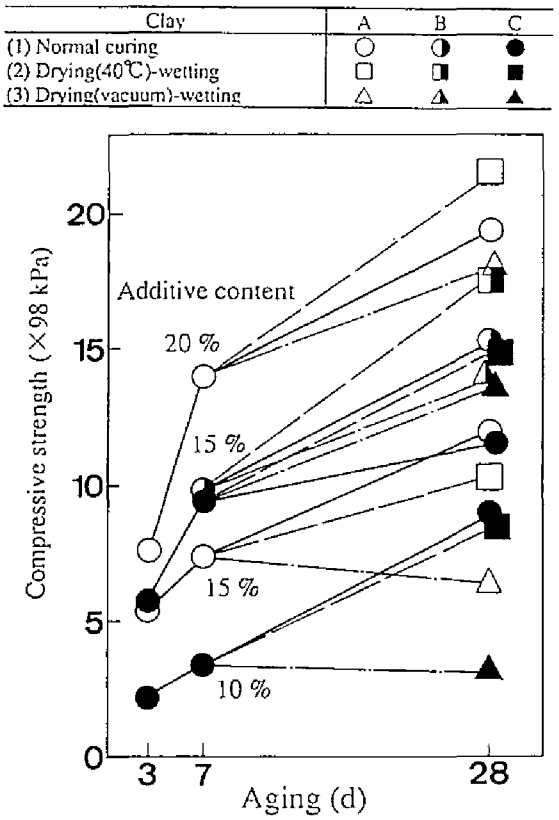


Fig. 3.11 Strength change of stabilized soil subjected to drying-wetting

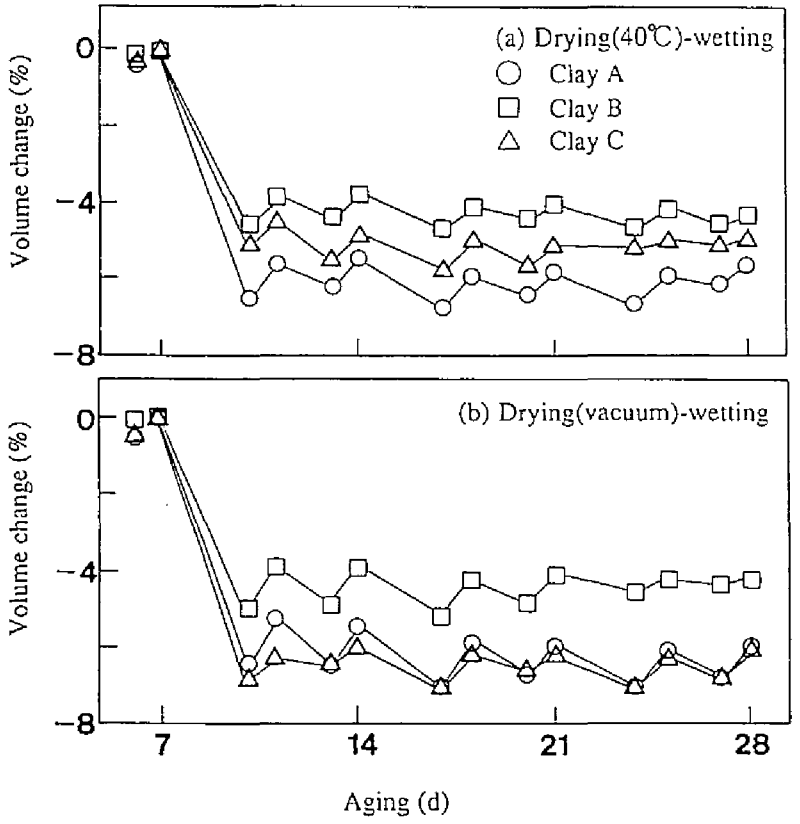


Fig. 3.12 Volume change of stabilized soil subjected to drying-wetting

and Soil A, and this agrees with the order of the liquid limit and the plastic index of the soils as well. From the volume changes under repeated cycles of drying and wetting, shown in Fig. 3.12, it is thought that the shrinkage due to drying may have a influence on the drying-wetting durability of the stabilized soils. In addition, the order of shrinkage was also in agreement with the order of durability. The shrinkage of the soils is believed to be strongly reflected by the clay content, the mineral composition, and other properties, as summarized by Kamon and Asakawa (1988) and Mitchell (1992). It can be concluded that the drying-wetting durability depends on the properties of the soil to be stabilized, such as the liquid limit and the plastic index. The accumulation of repeated strain due to drying and wetting leads to the deterioration of the material properties.

The influence that the water content has on the drying-wetting can be evaluated from Fig. 3.13, in which Soil A, with three levels of water content, was stabilized and then subjected to drying-wetting conditions. Although it was clarified in Fig. 3.11 that the stabilized soil with a higher 7-day strength than 900 kPa is stable against drying-wetting, a remarkable decrease in strength of the stabilized soil (115% water content, 20% cement addition) was detected due to the *Drying(vacuum)-wetting* cycles, in spite of a high 7-day strength of 1200 kPa. Stabilized

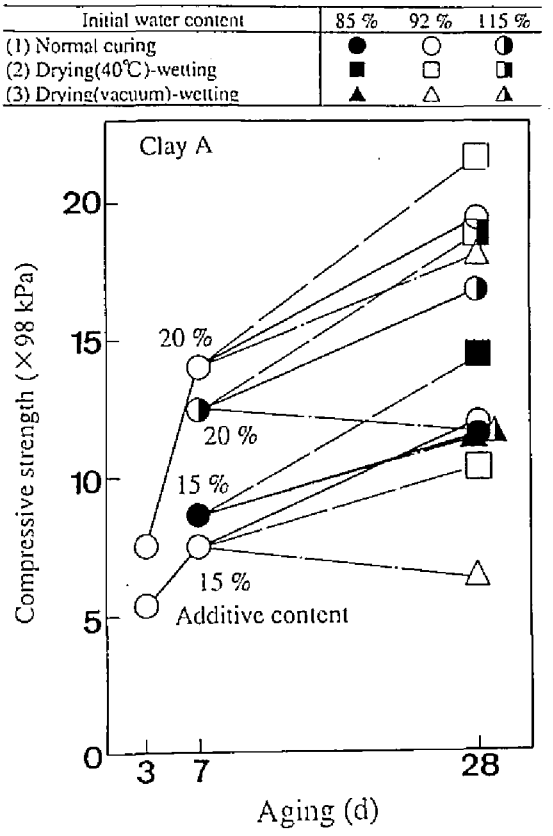


Fig. 3.13 Strength change of stabilized soil subjected to drying-wetting

soil with an 85% water content and a 15% cement addition had a similar strength level to the soil with a 92% water content. The strength of the former was greatly heightened by the drying-wetting, while the latter deteriorated in strength due to drying-wetting. It can be concluded, therefore, that the water content of a soil as well as the developed strength affects the drying-wetting durability.

Figure 3.14 shows the strengths of the soil stabilized by three types of stabilizers and subjected to drying-wetting. Stabilizer II showed a remarkable decrease in strength under drying-wetting conditions. The reason for this is that the sodium carbonate (Na_2CO_3) of the stabilizer component contributes to the hardening reaction due to the formation of carbonate salt, such as calcium carbonate, and the carbonate salt solves into the water. Consequently, this has a negative effect on the durability against drying-wetting. Stabilizer I produced a more durable mixture than the other two stabilizers. This is because the addition of FCA works to reduce the water content while it can not directly or chemically contribute to the hardening reaction.

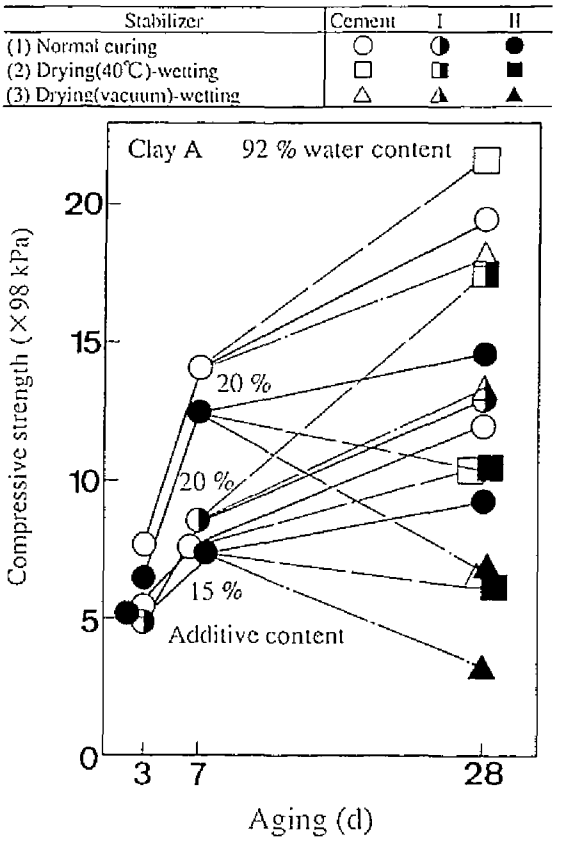


Fig. 3.14 Strength change of stabilized soil subjected to drying-wetting

3.4 Utilization System of Waste Sludge from Construction Works

3.4.1 New Utilization System of Waste Slurry

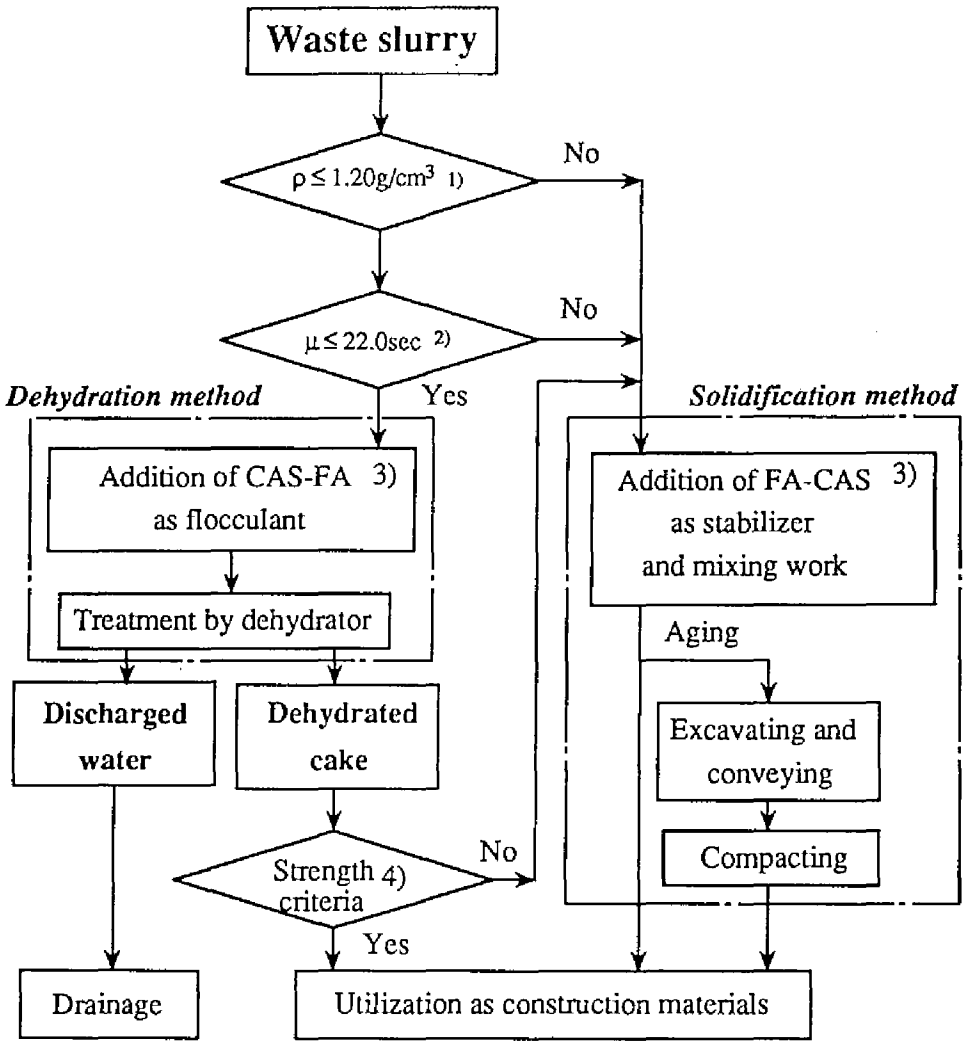
(1) Outline for Utilization System of Waste Slurry

Waste slurry is a mixture of excavated soil and water and is discharged from many kinds of excavation works. Generally, it contains many fine particles and is difficult to dehydrate rapidly. In the case of slurry excavation methods in which bentonite or polymers such as carboxyl-methyl cellulose (CMC) are often used for regulating viscosity, these dispersants remain in the waste slurry. Therefore, the slurry is very difficult to dehydrate. In solidifying slurry, a large amount of hardening agent (e.g., cement) is needed to solidify the waste slurry in order to attain the proper strength.

In order to solve this problem we propose a new utilization system for waste slurry. The conceptual outline of the system is shown in Fig. 3.15 (Kamon and Katsumi 1994). It is seen that this system consists of parallel dehydration and solidification methods which result in such resources as efficiency, a decrease in volume, stability, and recycling. It is proposed that the waste slurry, to which a kind of Carbonated-Aluminate Salt (CAS) and FCA is added as flocculants, should be dehydrated for volume reduction. The dehydrated cakes can easily attain the strength criteria set down by the Ministry of Construction, especially when using a high pressure dehydrator. Therefore, these dehydrated cakes can be directly applied as embankment and/or subgrade materials. Also, the discharged water satisfies the environmental standards for the potential of hydrogen (pH) and suspended solids (SS). In the solidification method, it is suggested that the slurry be stabilized by CAS and FCA to increase the strength for embankment or subgrade purposes. The use of FCA can be very effective from both a technical and an economical point of view.

(2) Selection of Treatment Methods

The selection between the two above-mentioned methods is based on the character of the waste slurry. Founded on the experience gained from dehydration experiments and various kinds of dehydration properties of waste slurries, it has been proposed that density (ρ) and viscosity (μ) be used as the criteria for the selection. The viscosity is a funnel viscosity measured with a 500 ml-funnel according to American Petroleum Institute standards. These parameters are universally measured to control the character of the slurry at excavation sites. Figure 3.16 shows three different kinds of slurry (A, B, and C) with independent ρ–μ characteristics due to the containment of CMC, bentonite, and soil particles. The solid content indicated by the density of the slurries and the funnel viscosity increased by the remaining bentonite and CMC can show the possibility for the effectiveness of the dehydration treatment. An attempt to reduce the volume by dehydrating a high solid content slurry is not always the best strategy from technical and economical viewpoints. Slurries with a low density can be dehydrated easily. However, if the slurries have a high viscosity due to dispersant remnants, the slurries then are difficult to



Note

1) ρ; density of waste slurry.
2) μ; funnel viscosity with 500 cc-funnel of waste slurry.
3) CAS; Carbonated-Aluminate Salt.
   FA; Fluidized bed combustion coal ash.
4) Strength criteria; $q_c \geq 2.0\ kgf/cm^2$ (=196kPa) or
   $q_u \geq 0.5\ kgf/cm^2$ (=49kPa)

Fig. 3.15 Outline for utilization system of waste slurry

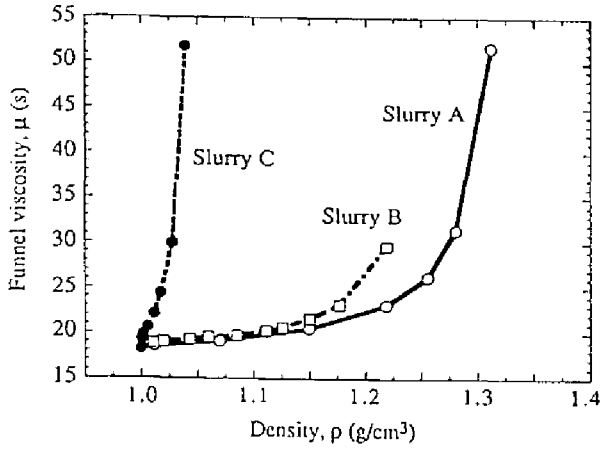


Fig. 3.16 Relationship between density and viscosity of slurry

Table 3.12 Composition of Carbonated-Aluminate Salt (CAS)

	CAS stabilizer	CAS flocculant
Portland cement	50 %	7 %
$Ca(OH)_2$	8 %	-
$CaSO_4$	9 %	-
$CaCO_3$	-	30 %
$Al_2(SO_4)_3$	6 %	40 %
Na_2CO_3	2 %	21 %
Blast furnace slag	25 %	-
Anionic polymer	-	2 %

dehydrate. Given the above parameters, waste slurries with a ρ-value higher than 1.2 g/cm^3 or a μ-value higher than 22 seconds can be treated effectively by solidification.

(3) Materials

CAS used as flocculating and hardening agents are differential mixtures of Portland cement, namely, $Al_2(SO_4)_3$, Na_2CO_3, $CaSO_4$, and so on (shown in Table 3.12). The effectiveness of CAS as a hardening agent was addressed in Sections 2.3 and 2.4. The newly developed CAS flocculant has the following properties:

(1) rapid flocculation,
(2) neutrality (pH = 5.0-9.0),
(3) impossibility of contamination by organic matter or chlorine compounds due to its composition,
(4) simple operating management due to the non-existence of an optimum additive content.

The FCA used in this study is derived from the fluidized bed combustion system discussed in Section 2.3. FCA contains gypsum and lime because of the use of a desulphurizer and an incomplete oxidation reaction in the combustion method. The properties of the FCA used here were presented in Table 3.10. It is important to assess the environmental impact induced by the utilization of waste materials such as FCA. The leachate levels of harmful components from

Table 3.13 Waste slurry samples used

Sample	Origin
Waste slurry A	shield tunnel work
Waste slurry B	shield tunnel work
Waste slurry C	cast-in-place concrete pile work
Waste slurry D	mixture of bentonite and water
Waste slurry E	cast-in-place concrete pile work
Waste water A	sludge dredged in a river
Waste water B	by erosion of laterite ground
Waste water C	muddy pond water

FCA are very low against the environmental quality standards. It can be applied effectively, therefore, in a utilization system for waste slurry without concern for the environmental impact.

In order to evaluate the effectiveness of this system, test studies were carried out on the waste slurry samples illustrated in Table 3.13.

3.4.2 Dehydration Method by a New Flocculant

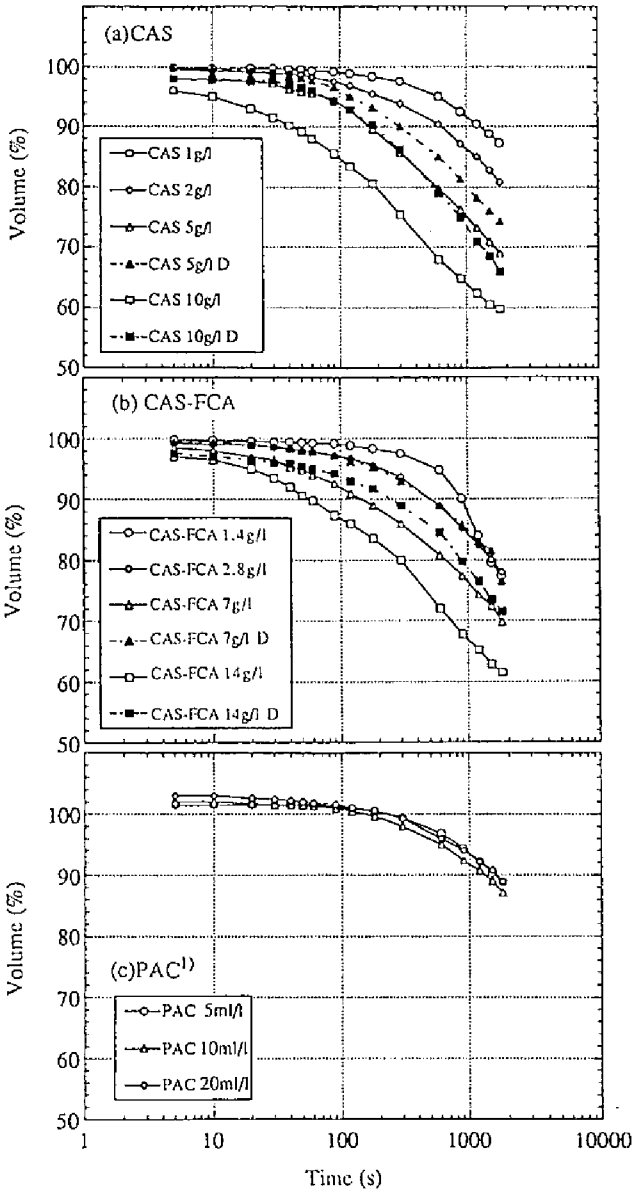
(1) Flocculation and Dehydration Characteristics

The addition of CAS and CAS-FCA (a mixture of CAS and FCA at a ratio of 5:2) causes the immediate formation of flocs 0.5-1.0 mm in diameter and a distinct boundary between solid (flocs) and water, while the slurries with PAC or $Fe_2(SO_4)_3$ have flocs which are too small to allow the observation of the separation of the water phase from the slurry. In this case, the slurry has a density under 1.1 g/cm^3.

As shown in Fig. 3.17, typical floc sedimentation characteristics measured with 1000 ml mess cylinder, CAS and CAS-FCA have a better improvability rate in sedimentation than the other flocculants. Although the tendency for sedimentation is less effective and remains unchanged in spite of the variation in the additive contents of PAC, an increase in CAS and CAS-FCA causes the formation of larger flocs, and consequently, efficient sedimentation. Due to the close relation between the amount of additive and flocculation, CAS is thought to be more practical for use in dehydration plants from an operational management point of view.

It is important to investigate the durability of flocs formed when the slurry is transported in dehydration plants. Although the flocs formed by CAS are completely destroyed within 5 minutes by the churning of an agitator, flocs are reformed by halting the churning of the slurry. A small decrease in sedimentation velocity is caused by churning, as shown in Fig. 3.17. Nonetheless, it is determined that the flocs produced by CAS and CAS-FCA are durable enough to be used in dehydration plants.

Consolidation tests on samples 6 cm in diameter by 6 cm in height were carried out with an oedometer on sludge sedimented for 30 minutes. The dehydration of slurry with a low density (Fig. 3.18 (a)), was achieved with CAS and CAS-FCA by compression because of the large and strong flocs. Many of the suspended solids were intermixed with discharged water, not having been separated well with PAC, which will be discussed in Section 3.4.2 (3). According

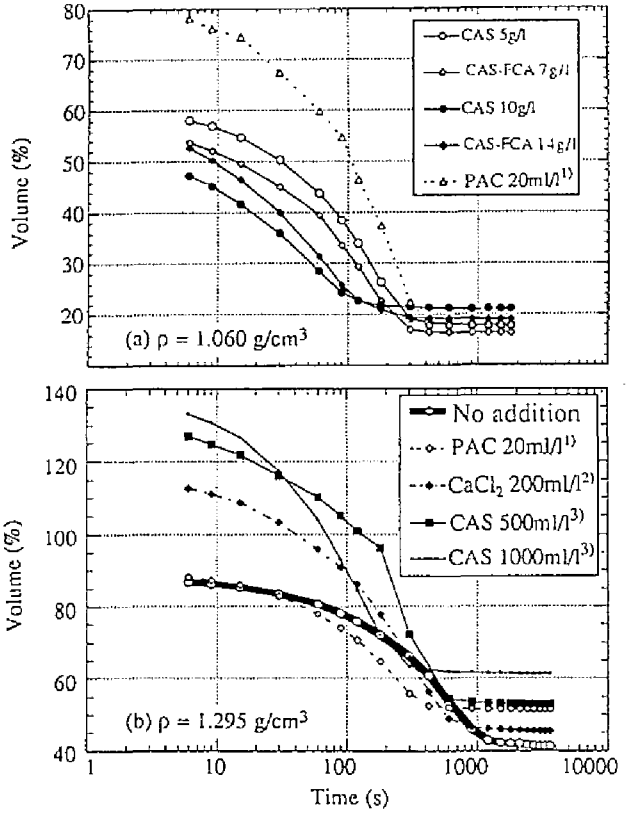


Waste slurry A : ρ = 1.060 g/cm^3; μ = 19.2 s
1) : with 10 ml/l addition of Polymer B 0.01 % solution
D : the slurries obtained through churning test

Fig. 3.17 Sedimentation characteristics of Waste slurry A with flocculants

to the examples of compression curves shown in Fig. 3.18 (a), it takes 5-10 minutes for the slurry with CAS to reach its final volume by compression, which is applicable to a practical dehydrator.

It is believed that the improvability of CAS depends on the density level of the slurry. In treating high density slurry, as shown in Fig. 3.18 (b), CAS was not more effective than the other flocculants. Tables 3.14 and 3.15 indicate the possibility of dehydrating slurries by consolidation at various levels of density. The samples marked 'x' in the tables flocculated too



Consolidation pressure : 9.8 kPa
1) : with 10 ml/l addition of Polymer B 0.01 % solution
2) : with 20 ml/l addition of Polymer A 0.1 % solution
3) : 5 % CAS solution

Fig. 3.18 Consolidation curves of Waste slurry A with flocculants

Table 3.14 Property of dehydration by consolidation and consolidation time

Type of flocculant	Additive content	Density of slurry (g/cm^3)			
		1.210	1.184	1.144	1.116
-		40 (87.1)	-	-	-
CAS-FCA	28 g/l	30 (13.4)	25 (6.4)	×	-
CAS-FCA (L)	200 ml/l	×	×	12 (347)	8 (345)
PAC[1)]	20 ml/l	25 (9.0)	15 (133)	-	-
PAC[1)]	10 ml/l	-	-	12 (6250)	8 (284)

Sample: Waste slurry B
Consolidation pressure: 549 kPa (after 78 kPa for 5 minutes)
CAS-FCA (L): mixture of CAS-FCA and water (14:100)
Unbracketed numbers indicate the time (minute) to reach the final volume by compression, and bracketed numbers indicate the SS (mg/l) of discharged water.
"×" indicates that the samples flocculated too insufficiently to consolidate.
1) with 10 ml/l addition of Polymer B 0.01 % solution.

Table 3.15 Property of dehydration by consolidation and consolidation time

Type of flocculant	Additive content	Density of slurry (g/cm^3)				
		1.038	1.020	1.015	1.004	1.001
-		×	-	-	-	-
CAS	20 g/l	×	-	-	-	-
CAS (L)	600 ml/l	-	-	×	9 (215)	9 (0.5)
CAS (L)	200 ml/l	×	×	×	×	×
PAC	40 ml/l	×	×	×	×	×
PAC[1)]	40 ml/l	×	×	12 (1569)	8 (4.7)	8 (59.6)
PAC	10 ml/l	×	×	×	8 (3.7)	×
PAC[1)]	10 ml/l	×	×	×	8 (5.8)	7 (9.7)
$Fe_2(SO_4)_3$	200 ml/l	×	×	×	×	×
$Fe_2(SO_4)_3$[1)]	200 ml/l	×	×	13 (15.8)	8 (1.8)	7 (4.7)

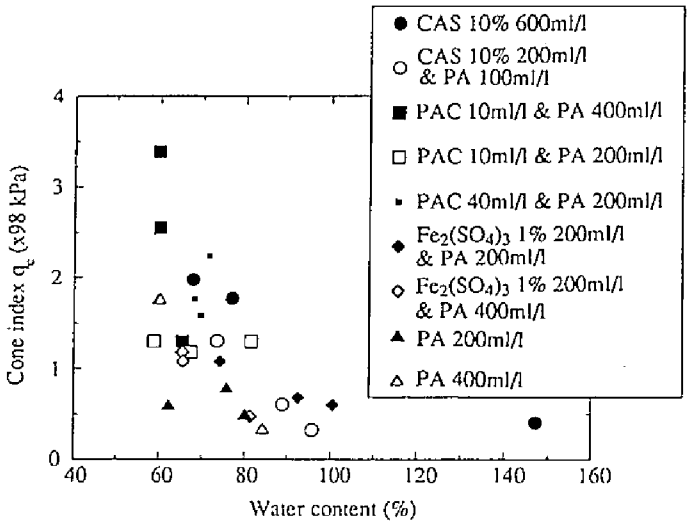
Sample: Waste slurry C
Consolidation pressure: 549 kPa (after 78 kPa for 5 minutes)
CAS (L): mixture of CAS and water (10:100)
Unbracketed numbers indicate the time (minute) to reach the final volume by compression, and bracketed numbers indicate the SS (mg/l) of discharged water.
"×" indicates that the samples flocculated too insufficiently to consolidate.
1) with 10 ml/l addition of Polymer A 0.1 % solution.

insufficiently to consolidate. CAS contributes to the improvability of low density slurry (Table 3.14). In the case of a slurry with a high viscosity level due to the remnants of CMC or bentonite, the flocculation will not come about by adding CAS (Table 3.15) even though it has low density. In order to dehydrate slurries containing bentonite, the bentonite must be gelled by the addition of flocculants. PAC and $Fe_2(SO_4)_3$ can cause the bentonite to gel because of cation exchange, and therefore, are more effective in the dehydration of bentonite slurry than CAS. In conclusion, it is very difficult to treat slurries with high density or high viscosity by the dehydration method from technical as well as economical viewpoints.

(2) Properties of Dehydrated Cakes

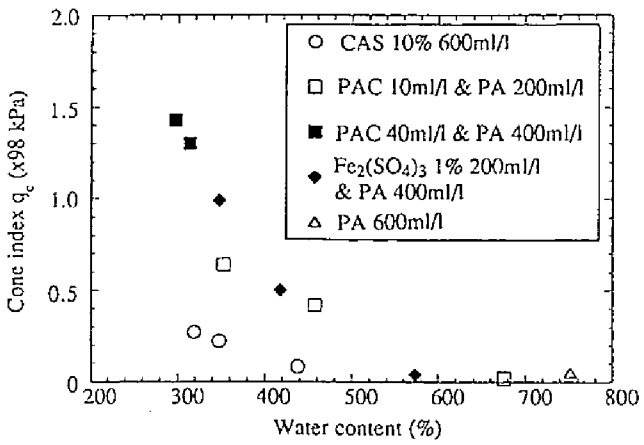
Figures 3.19 and 3.20 show the q_c values translated from fall-cone penetrations (60° tip angle and 60 g of mass) of the cakes dehydrated by a small-sized Filter-press test (Kamon et al. 1993). In the Filter-press system, the slurry (3000-5000 ml) was poured with flocculant into one a filtration compartment 12 cm in diameter and 3 cm in height for 60 minutes at an air pressure of 686 kPa. When treating Slurry B, the cakes treated by CAS had as high or higher strength than the cakes treated by the other flocculants. When slurry contains bentonite, the cakes treated by CAS are much lower in strength due to insufficient flocculation, as stated above.

It must be noted that the q_c values translated from the fall-cone penetrations differ from the values of the regulatory criteria set down by the Ministry of Construction, which classifies useful soil and waste sludge (q_c = 2 kgf/cm^2 = 196 kPa). Most of the cakes obtained from the small-sized Filter-press test can not fulfill the criteria for utilization as earthen materials. However, based on experimental research on the relationship between q_u and the fall-cone penetrations of the cakes dehydrated by Filter-press and Roller-press systems (Kita and Tsuji



Waste slurry B : ρ = 1.150 g/cm^3; μ = 21.5 s
PA : with addition of Polymer A 0.1 %

Fig. 3.19 Strength characteristics of cakes dehydrated by small-sized Filter-press tests



Waste slurry D : ρ = 1.011 g/cm^3; μ = 20.2 s
PA : with addition of Polymer A 0.1 %

Fig. 3.20 Strength characteristics of cakes dehydrated by small-sized Filter-press tests

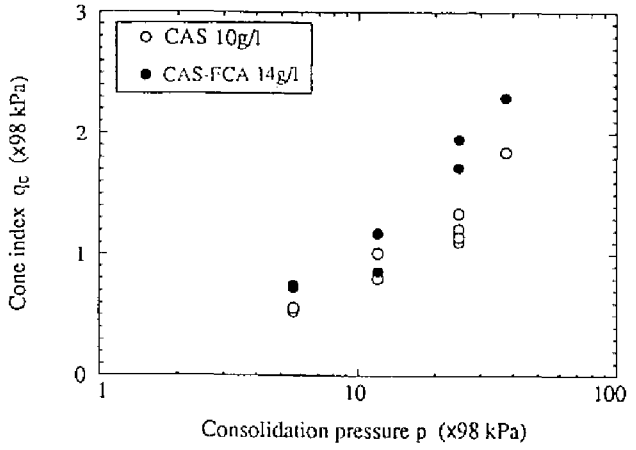


Fig. 3.21 Strength characteristics of dehydrated cakes

1981), a compressive strength of 0.5 kgf/cm^2 (= 49 kPa), the criteria of the Ministry of Construction, corresponds to about 2 mm of fall-cone penetration, which is translated to 140 kPa of q_c. Therefore, dehydrated soil cakes treated by CAS can be utilized for embankments or reclamation.

There are some strategies for obtaining cakes with higher strength. The dehydrated cakes treated by CAS-FCA have higher q_c values than the cakes treated by CAS only, as shown in Fig. 3.21. In this case, the q_c values of the cakes with CAS-FCA consolidated by high pressure (2.5 MPa) reach the criteria established by the Ministry of Construction. Although dehydration pressures in common dehydrator plants are equivalent to 0.5-1 MPa, the new Filter-press plants which achieve dehydration by a high pressure level of 4 MPa have been developed. Thus, a combination of CAS-FCA with high pressure Filter-press plants can produce dehydrated cakes directly utilized as earthen materials such as embankments, subgrade, and other similar applications.

(3) Properties of Discharged Water

In using CAS as a flocculant, the supernatant water and the discharged water satisfy the environmental quality standards (pH and SS), as shown in Table 3.16. The lack of turbidity in the discharged water depends on the effect of flocculant inducing flocculation. Since CAS flocs themselves and the formed flocs incorporate suspended soil particles, there are few SS remaining in the supernatant water. Due to the effect of the cation exchange, the discharged water treated by PAC and $Fe_2(SO_4)_3$ is both turbid and acidic. It is feared that by using PAC in Filter-press plants, excessive compression may result in the turbidity of the discharged water. It has been confirmed that the utilization of CAS contributes to water purification, such as BOD (biochemical oxygen demand), N (nitrogen), and P (phosphorus), as shown in Table 3.17.

Table 3.16 Quality of water discharged by sedimentation and consolidation tests

Sample	Type of flocculant	Additive content	Polymer additive content	Type of experiment	SS (mg/l)	pH
Waste slurry A (ρ = 1.06 g/cm^3)	CAS	1.0 g/l	-	S	2.6	-
		2.0 g/l	-	S	1.8	-
		10.0 g/l	-	S	3.5	-
	CAS-FCA	1.4 g/l	-	S	1.4	-
		2.8 g/l	-	S	1.4	-
		14.0 g/l	-	S	3.0	-
	PAC	20.0 ml/l	10 ml/l [2)]	S	428.4	-
	CAS	10.0 g/l	-	C	2.1	7.5
	CAS-FCA	14.0 g/l	-	C	4.0	7.8
	PAC	20.0 ml/l	10 ml/l [2)]	C	5644.3	4.4
Waste slurry B (ρ = 1.15 g/cm^3)	CAS (L)	600 ml/l	-	F	11.4	7.4
		200 ml/l	100 ml/l [3)]	F	27.6	7.6
	PAC	10 ml/l	400 ml/l [3)]	F	13.4	6.8
		10 ml/l	200 ml/l [3)]	F	168.0	7.0
		40 ml/l	200 ml/l [3)]	F	380.0	6.4
	$Fe_2(SO_4)_3$	200 ml/l	200 ml/l [3)]	F	0.1	7.0
		200 ml/l	400 ml/l [3)]	F	15.8	7.0
Waste water A	no addition	-	-	S	756.6	6.2
	CAS	0.1 g/l	-	S	9.1	6.8
		0.5 g/l	-	S	2.9	6.9
	$Fe_2(SO_4)_3$	0.1 g/l	50 ml/l [3)]	S	304.8	4.3
		0.5 g/l	50 ml/l [3)]	S	140.8	3.5
Waste water B	CAS	0.10 g/l	-	S	37.0	7.3
		0.15 g/l	-	S	31.0	7.2
		0.20 g/l	-	S	57.0	6.9
	PAC	1 ml/l	10 ml/l [2)]	S	5.0	7.0
		5 ml/l	10 ml/l [2)]	S	158.0	4.4
		10 ml/l	10 ml/l [2)]	S	468.0	4.1

1) S: sedimentation test, C: consolidation test, F: small-sized Filter-press test.
2) Polymer B 0.01 % solution
3) Polymer A 0.1 % solution

Table 3.17 Quality of waste water treated by CAS

	Laboratory tests		Field tests	
	untreated	treated	untreated	treated
pH	7.0	6.9	7.6	7.4
COD (mg/l)	7.5	4.0	2.6	1.0
BOD (mg/l)	3.0	1.0	4.0	2.0
T-N (mg/l)	8.7	0.9	0.75	0.57
T-P (mg/l)	0.19	0.02	0.11	0.01
T-Fe (mg/l)	1.9	0.09	1.7	0.52
Ca^{2+} (mg/l)	9.6	16.0	8.6	19.0
Turbidity (degree)	-	-	37	6

Sample: Waste water C

Naturally, not only these indexes but also heavy metals and other harmful components must be considered. Since it is merely that the waste slurry has a harmful composition, the dehydration method does not discharge the harmful treated water due to the leachate components of FCA and the well-known composition of CAS.

(4) Application of the Dehydration Method

CAS as a flocculant has been used at some construction sites on an experimental basis and the following advantages have been observed: simple execution management, peel-off characteristics of dehydrated cakes from filter cloth, and dehydration characteristics due to the low viscosity of slurry with CAS.

3.4.3 Solidification Method by Coal Ash Utilization

(1) Strength Characteristics

Table 3.18 illustrates the changes in strength for waste slurry discharged from a cast-in-place concrete pile work, mixed with FCA and CAS. In the case of CAS only, the strength required by the regulatory criteria of the Ministry of Construction can not be achieved in 7 days of curing even if the CAS content is raised as high as 25%. The strength of the waste slurry reaches 49 kPa, the criteria, when using a 70% FCA-13% CAS mixture cured for only 3 days. For

Table 3.18 Strengths of the slurry-FCA-CAS mixtures

Additive content (%)		Compressive strength (kPa)				Volume change ratio
FCA I	CAS	3 days	7 days	14 days	28 days	
40	7	-	65	199	228	1.20
	10	-	101	356	435	1.22
	13	19	142	629	761	1.24
50	4	-	73	172	219	1.26
	7	-	112	348	314	1.27
	10	15	175	534	665	1.28
	13	29	213	931	855	1.31
60	4	-	123	253	419	1.31
	7	-	194	411	637	1.32
	10	27	282	670	978	1.33
	13	40	396	1145	1381	1.34
70	4	15	215	493	467	1.36
	7	17	319	720	891	1.37
	10	38	435	980	1178	1.38
	13	61	579	1260	1711	1.39
0	10	-	13	15	30	1.02
	20	-	26	40	74	1.09
	25	-	40	67	98	1.10
	30	-	133	183	305	1.17

Note: Waste slurry C; ρ (density) = 1.04 g/cm^3, μ (funnel viscosity) = 51.7 s.
Additive content indicates the mix proportion to 100 % waste slurry.
Volume change ratio indicates the volume of slurry-FCA-CAS mixture after mixing versus the one of waste slurry only.
"-" indicates that the hardened strength is too low to measure the unconfined compressive strength.

embankment or subgrade purposes, it is suggested that the strength after 7 days of curing should be able to sustain 100-200 kPa of stress, and the required strength can be achieved when the FCA content and the CAS content are more than 40% and 10%, respectively. A decrease in the FCA content and/or an increase in the CAS content results in a larger growth in strength versus aging period. Therefore, it is possible to attain both early and late strength by adjusting the contents of FCA and CAS.

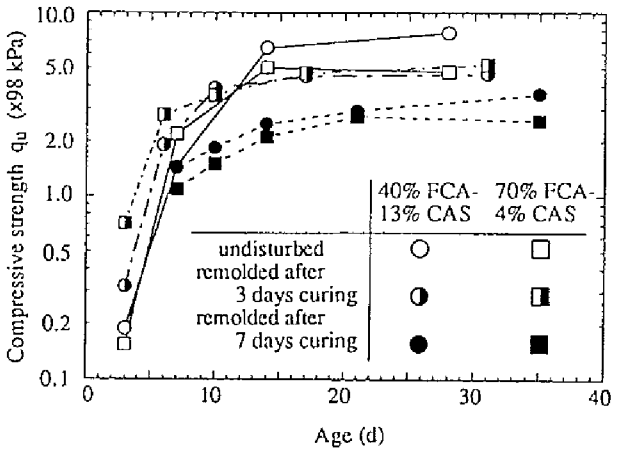
In this treatment method, the addition of FCA and CAS results in a volume increase of 20-40%, as shown in Table 3.18. This volume increase is relatively small in comparison to the additive amount of FCA, giving this method great efficiency in terms of coal ash utilization.

(2) Durability Characteristics

Figure 3.22 shows a comparison of strengths for samples remolded after 3 or 7 days of curing with undisturbed samples. Due to the increase in density caused by remolding and an incomplete hardening reaction, the mixtures remolded after 3 days of curing have higher strength levels during the early stages than the samples cured normally, namely, 100-200 kPa of strength after 3 days of curing after remolding, and can be considered for utilization as embankment or subgrade materials. In the soaking tests on samples cured normally for 7 days, neither a collapse nor a softening of the mixtures occurred. Taking durability into consideration, therefore, a slurry-FCA-CAS mixture can be used very effectively as ground material through the process of mixing, hardening, excavating, conveying, and compacting.

(3) Mixing Workability

In using CAS only, it is difficult to obtain homogeneous mixtures due to the high viscosity of slurry. The slurry-FCA-CAS mixture is uniform because of the affinity between slurry and FCA.



Waste slurry C : ρ = 1.040 g/cm^3; μ = 51.7 s

Fig. 3.22 Strength characteristics of slurry-coal ash-CAS mixtures

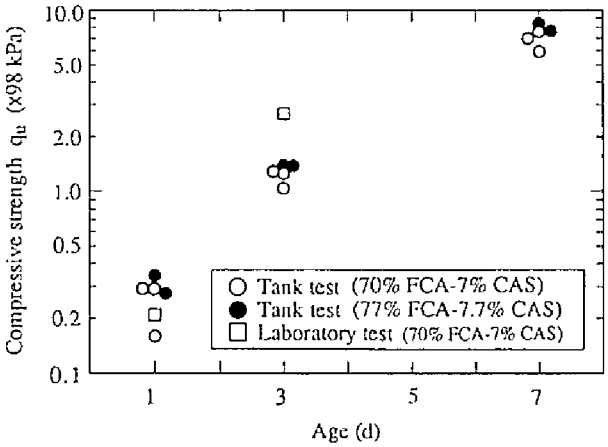


Fig. 3.23 Strengths of specimens sampled through the tank tests

Full scale tank tests were carried out to investigate the application of this solidification method in practice. Two tanks, 2.3m x 8.0m in width x 1.6m in depth were used, and a back hoe with an exclusive dipper (0.7 m^3 volume) adjacent to the tank conducted the mixing work. As the total volume of the waste slurry discharged from a cast-in-place concrete pile work was 12 m^3, it was decided that the additive contents in the tanks were to be 70% (8400 kg) FCA and 7% (840 kg) CAS for one tank, and 77% (9200 kg) FCA and 7.7% (920 kg) CAS for the other tank. After mixing for 40 minutes, the mixtures were kept undisturbed for 24 hours, 3 days, and 7 days.

The strength levels gained by the mixtures left for 24 hours were strong enough to safely permit walking on it. Figure 3.23 shows the strengths of the specimens sampled at various points in the tanks. The strength dispersion of the samples is within a small range in spite of the expected roughness of the mixing work due to the size of the dipper versus the tank. The ratios of the strengths sampled in the tanks versus the strengths obtained from the laboratory specimens are very high compared with the ratios for traditional soil stabilization. The strengths at 3 days and 7 days of curing were more than 100 kPa and 500 kPa, respectively. The mixtures have the potential for utilization as embankment and subgrade materials.

(4) Application of Solidification Method

The proposed solidification method cannot satisfy decreases in volume. In order to treat waste slurry with high density or high viscosity, however, coal-ash utilization leads to efficient and rapid treatment and is desirable from the viewpoint of recycling resources.

3.5 Conclusions

In this chapter, we discussed the stabilization of waste or surplus sludge discharged from construction works. Strength development characteristics with regard to hardening mechanisms and durability against drying-wetting were presented. The main results obtained can be summarized as follows:

(1) Through an evaluation of the hardening effects of cement and/or cement group materials, sludge with a high water content can be stabilized by hardening agents (about 200 kg/m^3 of additive content) so that the stabilized sludge can be utilized as an earthen material, such as subgrade or an embankment. The hardening mechanisms of sludge stabilization were distinctive, namely, calcium aluminate carbonated hydrate ($7CaO \cdot 2Al_2O_3 \cdot CaCO_3 \cdot 24H_2O$) was detected and is considered to contribute to strength development. The strength development characteristics are reflective of the type of stabilizer employed. Therefore, these effects have to be taken into account when sludge is solidified for utilization purposes.

(2) With regard to the drying-wetting conditions, the strain accumulation due to dry shrinkage and the disappearance of reactive products have an influence on the durability. These effects are strongly reflected by the developed strength as well as the soil properties, water content, and type of hardening agent. It was also clarified that the drying method which uses a vacuum desiccator can be effectively applied for the drying-wetting durability assessment.

(3) A system utilizing waste slurry which consists of dehydration or solidification was proposed. It was found that the density (ρ) and the funnel viscosity (μ) of the waste slurry can be used effectively as the indexes with which to judge the criteria of whether a slurry should best be treated by dehydration or by solidification for recycling purposes.

(4) CAS as a flocculant in the utilization system can form large and durable flocs rapidly. The flocs can be easily dehydrated and the discharged water is clear enough to satisfy environmental quality standards. Furthermore, a combination of CAS and FCA with the operation of a high pressure dehydrator can produce cakes which can then be directly utilized as embankment or subgrade materials.

(5) The solidification method using mixtures with FCA and CAS is very effective for treating high density or high viscosity waste slurry. Waste slurry which is mixed well with stabilizers is highly homogeneous and reasonably strong. It also has high durability under soaking or remolding conditions, so it can be used effectively as an embankment or subgrade material.

The utilization system is practicable in terms of the complete utilization of waste slurry as a construction material.

References for Chapter 3

Ministry of Health and Welfare, Japan (1995). *Handbook on industrial waste management*, 1995 version, 740p (in Japanese).

JCA (Japan Cement Association) (1994). *Manual on the ground improvement practice by cement-based-stabilizer, Gihohdo-shuppan*, 424p (in Japanese).

JSMS (Society of Materials Science, Japan) (1991). *Handbook on ground improvement method, Nikkan-Kogyo-Shinbunsya*, 530p (in Japanese).

Kajihara, H. and M. Kusumi (1994). "Production of bricks from turbid water treatment sludge," *Tsuchi-to-Kiso*, JSSMFE, Vol.42, No.10, pp.43-46 (in Japanese).

Kamon, M. (1978). "Engineering properties of Hedoro," *Tsuchi-to-Kiso*, JSSMFE, Vol.26, No.1, pp.19-24 (in Japanese).

Kamon, M., and M. Asakawa (1988). *Classification and physico-chemical property of soil*, Gihodo-shuppan, 271p.

Kamon, M. and T. Katsumi (1994). "Utilization of waste slurry from construction works," *Proc. 13th Int. Conf. on Soil Mech. and Foundation Engrg.*, Vol.4, pp.1613-1616.

Kamon, M., T. Katsumi and H. Imanishi (1993). "Treatment and utilization of waste slurry from construction works," *Annuals, Disas. Prev. Res. Inst., Kyoto Univ.*, No.36 B-2, pp.37-51 (in Japanese).

Kamon, M. and S. Nontananandh (1990). "Contribution of stainless-steel slag to the development of strength for seabed hedoro," *Soils and Foundations*, Vol.30, No.4, pp.63-72.

Kamon, M. and S. Nontananandh (1991). "Combining industrial wastes with lime for soil stabilization," *Jour. Geotech. Engrg.*, ASCE, Vol.117, No.1, pp.1-17.

Kamon, M., K. Sawa and S. Tomohisa (1989). "On stabilization of Hedoro by using cement group hardening materials," *Jour. Society of Materials Science, Japan*, Vol.38, No.432, pp.1092-1097 (in Japanese)

Kawachi, T., T. Katsumi, P.O. Tran Duc and M. Yamada (1996). "Treatment and utilization of waste sludge/slurry from construction works in Japan," *Proc. 2nd International Cong. on Environmental Geotechnics*, (in submitting).

Kawachi, T., N. Ogawa and H. Iso (1994). "Making of backed material from construction sludge," *Proc. 5th Annual Conf. of JSWME*, pp.200-202 (in Japanese).

Kita, D. and H. Tsuji (1981). "Treatment and utilization of discharged slurry from slurry excavation methods," *Tsuchi-to-Kiso*, JSSMFE, Vol.29, No.11, pp.57-64 (in Japanese).

Kujala, K. (1989). "Stabilization of harmful wastes and muds," *Proc. 2nd Int. Symp. on Environmental Geotechnology*, Shanghai, Vol.1, pp.540-548.

Kutara, K., Miki, H., Y. and Y. Okada (1984). "Effect of humic acid in soil on increase in strength of stabilized soil," *Civil Engrg. Jour.*, PWRI, Ministry of Construction, Vol.26,

No.8, pp.405-410 (in Japanese).

Miki, H., Y. Hayashi and N. Aoyama (1992). "Development of new techniques to heighten the value of soil materials," *Civil Engrg. Jour.*, PWRI, Ministry of Construction, Vol.34, No.11, pp.58-65 (in Japanese).

Miki, H., T. Yamada, H. Ichiyanagi and H. Shinsya (1994). "Geotextile tube dehydration method for dredged soil," *Tsuchi-to-Kiso,* JSSMFE, Vol.42, No.10, pp.31-34 (in Japanese).

Ministry of Construction (1995). *Investigation on generation and management of by-product from construction works* (in Japanese).

Mitchell, J.K. (1992). *Fundamentals of soil behavior,* Second edition, John Wiley & Sons, Inc., 437p.

Morgenstern, N.R. (1995). "Geotechnics of fine tailings management," *Geoenvironment 2000,* Geotechnical Special Publication No.46, ASCE, pp.1663-1683.

Naemura, S. and N. Ogawa (1992). "Recycling treatment method of construction sludge," *Civil Engrg. Jour.*, PWRI, Ministry of Construction, Vol.34, No.11, pp.52-57 (in Japanese).

Ogino, T., T. Goto, K. Kataoka and M. Kuroda (1994). "Utilization of stabilized dredged waste for construction materials," *1st Int. Cong. on Environ. Geotechnics*, Edmonton, pp.49-56.

Rollings, M.P. (1994). "Geotechnical considerations in dredged material management," *1st Int. Cong. on Environ. Geotechnics*, Edmonton, pp.21-32.

Shimoda, M, T. Yamamoto, S. Nakamura and Y. Okada (1990). "Durability of soil quicklime stabilization," *Proc. 25th JSSMFE,* pp.1931-1932 (in Japanese).

Takano, Y., and K. Sakamaki (1984). "Durability of the soil stabilized by the cement based stabilizer," *Proc. 38th General Meeting of CAJ,* pp.528-531 (in Japanese).

Tanaka, M., S. Saito, M. Hara, Y. Shibata and Y. Okita (1994). "Melting treatment and utilization of sludge from slurry excavation method," *Proc. 1st Nat. Symp. on Environmental Geotechnology,* JSSMFE, pp.261-266 (in Japanese).

Tashiro, C., J. Oba and K. Akama (1979). "The effects of several heavy metal oxides on the formation of Ettringite and the microstructure of hardened Ettringite, *Cement and Concrete Res.*, Vol.9, pp.303-308.

Tay, J.H. and K.Y. Show (1990). "Properties of cement made from sludge," *Jour. Environ. Engrg.*, ASCE, Vol.117, No.2, pp.236-246.

Zyl, D.V. (1993). "Mine waste disposal," *Geotechnical Practice for Waste Disposal*, D.E. Daniel (Ed.), Chapman & Hall, Chapter 12, pp.269-286.

CHAPTER 4

New Strategy for both Waste Utilization and Environmental Mitigation

4.1 General Remarks

Many efforts have been made in the research and development of waste utilization in the field of geotechnical engineering, although there are still many obstacles. New strategies for supplemental or advantageous management are required, therefore, in order to promote geotechnical waste utilization. Of the new strategies, some technical methods, such as liquefied soil stabilization, light weight soil stabilization, and geotextile tube dehydration, have been proposed to allow for the utilization of surplus soil, waste sludge and slurry, and other similar materials in Japan, as stated in Section 3.2. The "Liquefied soil stabilization method," in which soil mixtures are blended with a stabilizer and a large amount of water, has flowability and hardening characteristics, and is available for filling in underground pipe constructions or backfill retaining walls (Kuno et al. 1992). The "Light weight soil stabilization method," in which surplus soils are mixed with lightweight materials, such as EPS or foamed cement, is expected to be applied as embankment and backfill materials (Pradhan et al. 1995). The "Geotextile tube dehydration method," in which dredged sludge is dehydrated by being poured into a geotextile tube and aged, is proposed for application to river embankments (Miki et al. 1992).

In this chapter, a new technical method referred to as the "Bagged WRP Method" which utilizes a by-product, waste rock powder (WRP), will be proposed from the aspect of waste utilization as well as environmental mitigation. In the method, woven and/or non-woven fabric bags filled with a dry mixture of WRP and hardening agents are solidified by soaking. If the bagged and solidified WRP can be placed on the seafloor and function as a sunken levee, the method will not only allow for geotechnical waste utilization, but also for environmental creation due to the construction of man-made tidal flats behind the sunken levee, as shown in Fig. 4.1.

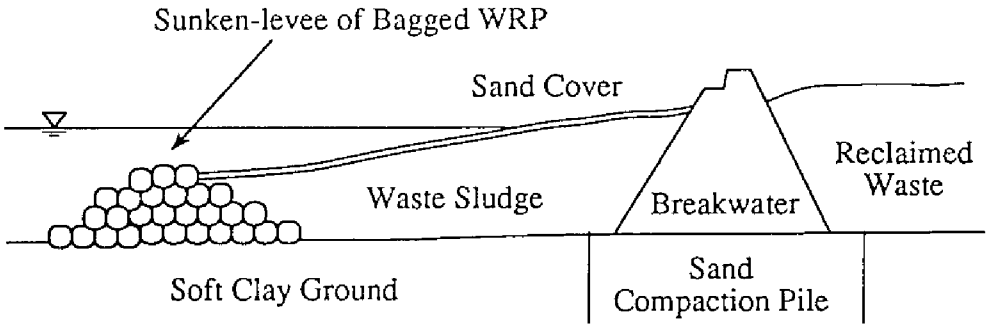


Fig. 4.1 Application of the Bagged WRP Method to tidal flat construction

In the following sections of this chapter, the effectiveness and the applicability of the "Bagged WRP Method" are discussed using results from both experimental studies and the analytical approach. Prior to a presentation on the applicability of the method, the present conditions of the generation and management of WRP will be reviewed, and coastal development and environmental mitigation will be addressed in Section 4.2. In Section 4.3, the fundamental properties of WRP solidified by a newly developed hardening agent, one kind of Carbonated Aluminate Salt (CAS), is introduced and the applicability of the stabilized WRP to geotechnical purposes is mentioned. Engineering characteristics and the environmental impact of bagged WRP will be discussed through laboratory studies as well as field tests. A parametric analysis of the stability of a sunken levee and the seafloor is conducted in order to determine the applicability of the "Bagged WRP Method." to coastal development and mitigation.

4.2 Background

4.2.1 Generation of Waste Rock Powder

Waste rock powder (WRP), also called quarry dust, is one kind of by-product discharged from rock crusher plants. Due to environmental constraints placed on the use of natural gravel for the construction industry, alternative sources or methods are required to fulfill the role played by natural gravel. One alternative source is the rubble produced in crusher plants nationwide. Japan produces approximately 500 Tg of rubble and 10 Tg of WRP as by-products annually. Although WRP is non-hazardous in nature, it is considered an "industrial waste" under the Japanese legal system. Therefore, its utilization has been limited to filling material for exhausted diggings of the mother rock of rubble or it is simply disposed of. Taking into account the scarcity of disposal sites, a suitable method for solidifying and utilizing this WRP in large quantities is needed.

WRP is a powder, similar in condition to slag and fly ash. However, WRP is not a

pozzolanic material which leads to a hardening reaction. WRP, surplus soil, and discharged waste slurry all originate from the ground, but WRP is easier to handle because much of the WRP is in a dry state. The characteristics of WRP depend on the mother rock; the WRP of limestone is used as a raw material for cement due to its chemical composition, while the silty WRP of sandstone is reused as a filling material in exhausted diggings. The WRP of sandstone, with a large specific surface area and a great amount of amorphous materials, increases the effect of lime stabilization in soils in which a low proportion of fine particles or amorphous materials is present (Nishida et al. 1992).

4.2.2 Coastal Development and Environmental Mitigation

Many projects for infrastructures have been completed, are on going, or are being planned for coastal areas of Japan. Recently, the topic of environmental preservation has been raised because of these coastal developments. It is necessary, therefore, to minimize environmental damage and achieve sustainable development, and thus, the concept on Environmental Mitigation has been addressed. For example, landmarks created by a mountain of waste materials was proposed from the standpoint of waste landfills and the creation of a new environment (Committee on the Waterfront Development by LANDFILL 1995).

In the last decade, about 40% of tidal flat areas in Japan have disappeared due to reclamation or dredging works. Thus, the construction of man-made tidal flats is also an important option for environmental mitigation in coastal areas. The man-made tidal flats will become a substitute for those which will be destroyed by reclamation or dredging works. Tidal flats preserve ecosystems and add to the purification of the sea environment, fish production, resort spots, and other waste reclamation areas, as stated by Fukuda et al. (1992). Waste materials can be applied to reclamation projects filling to construct the tidal flats, as proposed by Hamasuna (1992). Sunken-levee construction is essential for retaining soil materials in tidal flats. The Bagged WRP Method represents a useful new strategy for both waste management and environmental mitigation (Kamon and Katsumi 1994 and 1995).

4.3 Engineering Properties of Bagged WRP

4.3.1 Properties of the Materials

(1) WRP

The characteristics of WRP depend on the type of machinery used for crushing and collecting as well as the properties of the mother stone. WRP is generated from the crusher for rock crush and sand production in both dry and wet conditions.

The WRP used in this study is a by-product generated through rock crushed under dry conditions. Its properties are shown in Table 4.1. The mother stone is liparite, and the main minerals investigated through X-ray diffraction analyses are quartz, feldspar, and amesite. The

Table 4.1 Properties of WRP

Particle density (g/cm^3)	2.65
Liquid limit (%)	14.3
Plastic limit (%)	NP
Optimum moisture content (%)	13.0
Maximum dry density (g/cm^3)	1.97
Particle size distribution	
Sand fraction (%)	16.8
Silt fraction (%)	70.4
Clay fraction (%)	12.8
D_{60} (mm)	0.031
D_{30} (mm)	0.009
D_{10} (mm)	0.004
Uniformity coefficient U_cC	7.75
Coefficient of curvature U_c'	0.65
Ignition loss (%)	1.35
Chemical compositions (%)	
SiO_2	65 - 75
Al_2O_3	10 - 15
Fe_2O_3	3 - 4
Na_2O	2 - 3
K_2O	1 - 2
Main minerals	Quartz Feldspar Amesite

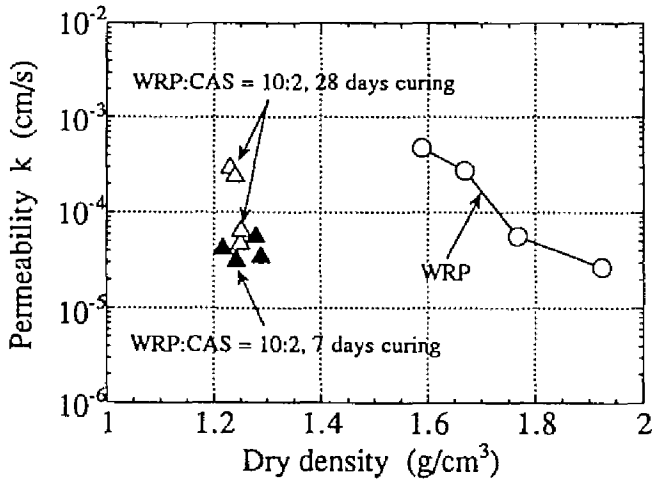


Fig. 4.2 Permeability of WRP and WRP-CAS mixtures

WRP is composed of particles equivalent to the size of silt grains, and judging from the uniformity coefficient and coefficient of curvature, the WRP is poor in particle size distribution. Moreover, the optimum moisture content is near the liquid limit. Since the WRP is very difficult to manage by means of compaction, therefore, the noncompacted method is recommended for WRP solidification. As the permeability of WRP is in the range of 10^{-3} to 10^{-5} cm/s, as shown in Fig. 4.2, WRP is considered to be a permeable material and the noncompacted method can promote its utilization as a well-drained material if the stabilized mixture is as permeable as untreated WRP.

(2) CAS

One kind of CAS is used as a hardening agent. It has previously been shown that CAS is effective as a hardening material for soft clays or waste materials, as stated in Chapters 2 and 3. The CAS used in this study has the composition of Ordinary Portland Cement (OPC) : $Ca(OH)_2$: $Al_2(SO_4)_3$ = 5 : 2 : 3 (dry weight basis). The hydrated reaction of it leads to the immediate formation of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$), and the hardening and expansion of CAS occur right after watering.

4.3.2 Basic Characteristics of WRP-CAS Mixtures

(1) Expansion Characteristics

CAS, used as a hardening material in this study, leads to the rapid formation of ettringite and other hydrates, and consequently, not only hardens but also expands with watering. Mehta (1976) clarified the expansive mechanisms of cement concrete associated with the formation of ettringite. Therefore, it is important to investigate the expansion characteristics of WRP-CAS mixtures. Figure 4.3 illustrates expansive pressure versus watering time ratios of the mixtures. In this experiment, the consolidation mold (6 cm in diameter and 2 cm in height) was filled with a dry mixture and soaked while the pedestal remained stationary and the expansive pressure was

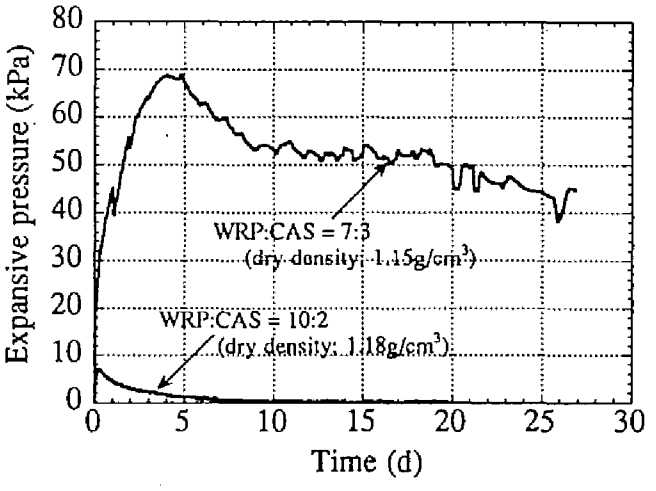


Fig. 4.3 Expansive pressure of WRP-CAS in watering

continuously measured. It is thought that the expansive pressure depends on the CAS content and the dry density of the mixture. In this case, the two mixtures have similar dry densities, 1.15 g/cm^3 and 1.18 g/cm^3. The expansive pressure-time curves for the two mixtures both have one peak and show a similar trend. When WRP:CAS = 10:2, the expansive pressure maximum is only about 8 kPa per day, while the WRP:CAS = 7:3 mixture has a maximum expansive pressure of 70 kPa after 4 days of curing.

The expansive characteristics of the stabilized mixture have some advantages, namely, the mixture can be stabilized at a low density and shrinkage is avoided when it is used as a filling material. To prevent harm to the surrounding structure, if the mixture is applied to earthen materials, it is possible and necessary to control expansion by adjusting the CAS content and density.

(2) Strength and Density Characteristics

Specimens for unconfined compressive strength tests were basically prepared according to the Practice for Making and Curing Noncompacted Stabilized Soil Specimens (JGS T 821-1990). The dry mixture of WRP, which is finer than 2 mm, and stabilizers, such as CAS and OPC, were poured into a cylindrical mold (10 cm in height and 5 or 5.6 cm in diameter), aiming at a level of dry density in the range 1.2-1.4 g/cm^3. The mold (filled with the mixture) was then soaked while the exposed upper side of the mold was covered by filter paper for water transmission and loaded at 10-20 kPa to prevent harmful expansion.

Figure 4.4 shows the strengths of the WRP mixtures which were stabilized by CAS and OPC and cured for 7 days. There is a clear correlation between the strengths and the densities of the mixtures. The WRP-OPC mixtures have a higher strength and a greater density than the WRP-CAS, because these stabilizers have different reaction mechanisms. OPC, when used as a stabilizer, dissolves by means of watering, and hardens after a minimum of 1 day of curing. Thus, the mixture shrinks and the density increases to 1.4-1.6 g/cm^3, higher than the target density of 1.2-1.4 g/cm^3. The WRP-CAS mixtures harden rapidly and tend to expand by the immediate formation of ettringite as soon as the dry mixtures are soaked. As a result, the desired low densities of 1.2-1.4 g/cm^3 were kept as they were. Observations of the mixtures in early time frames prove these phenomena. After only 1 hour of watering, the WRP-OPC mixtures formed a slurry, but the WRP-CAS mixtures had already hardened.

Increases in the CAS content as well as the dry density result in an increase in strength. The mixtures of WRP:CAS = 7:3 exhibit higher strengths than 1 MPa and can be utilized as subbase materials. On the other hand, the strengths of WRP:CAS = 8:2 and WRP:CAS = 10:2 are in the range of 500 kPa to 1 MPa and these mixtures are considered to be available for use as subgrade or embankment materials.

The relationship between the strength and the curing time of each WRP-CAS mixture is illustrated in Fig. 4.5. As is the case with general stabilized soil, curing causes an increase in strength, and the strength depends more on the effect of the curing time than the dry density.

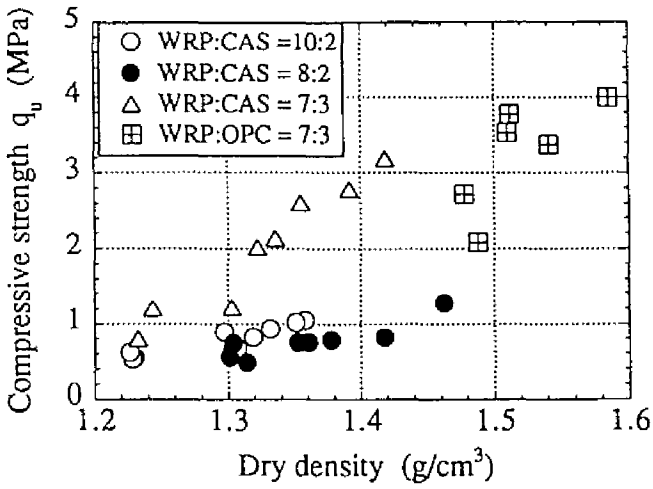


Fig. 4.4 Strengths of WRP mixtures cured for 7days

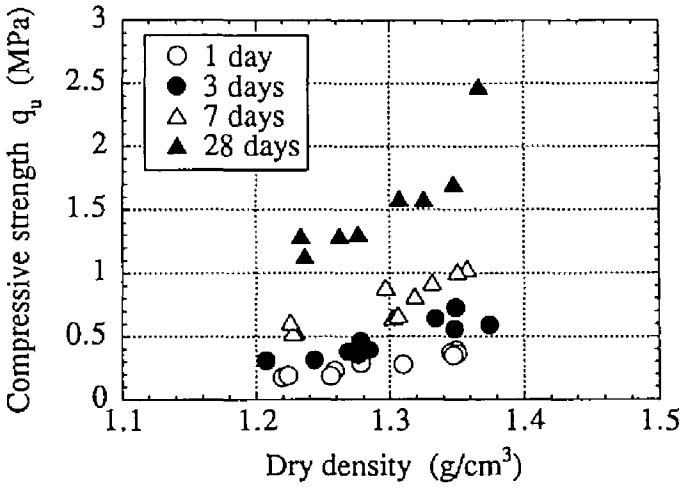


Fig. 4.5 Strengths of WRP-CAS mixtures (WRP:CAS = 10:2)

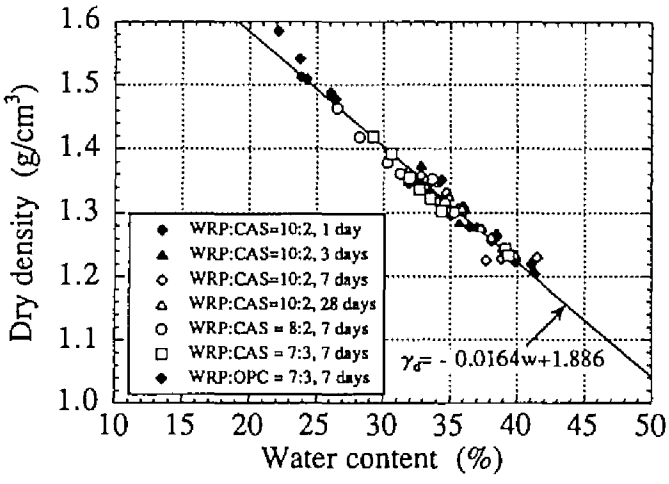


Fig. 4.6 Dry density versus water content of WRP mixtures

Although the WRP-CAS mixtures can not attain a stress of 1 MPa for subbase purposes, the specimens cured for 1 day have higher strength values than 100 kPa. Therefore, this stabilization method makes not only waste treatment possible, but also the utilization of WRP as an earthen material such as embankments or backfilling.

Figure 4.6 shows the relation between the dry density (ρ_d) and the water content (w) for each mixture. The strong correlation between these indexes is independent of the types and contents of the stabilizers and curing times, and presents the following regressive equation:

$$\rho_d = 1.886 - 0.0164w \quad (R = 0.995) . \qquad \text{(Eq. 4.1)}$$

It is easy to measure the water content of specimens sampled at the site, and the unconfined compressive strength can be estimated from the mixtures, curing time, and dry density from the equation based on water content.

(3) Permeability

Specimens for permeability tests were prepared by the same procedure as specimens prepared for the unconfined compressive strength tests. Falling head permeability tests were carried out according to the Test Method for Permeability of Saturated Soils (JGS T 311-1990).

The results of the permeability tests are shown in Fig. 4.2. The WRP-CAS mixtures with a density of 1.2-1.3 g/cm^3 exhibit about 10^{-4} cm/s of permeability; therefore, the mixtures can be utilized as well-drained materials. Although the permeability depends on the raw materials and the stabilization method, some general soils stabilized by hardening materials such as cement or lime exhibit a permeability below 10^{-6} cm/s and some reach a permeability of 10^{-8} cm/s for the cut-off of water. At present, it is said that the development of permeable ground materials for construction is needed for water circulation from the standpoint of environmental geotechnology. Due to the high degree of technology, permeable pavement system, group-grained coal ash utilization, and so on have been developed as permeable materials. The method proposed in this study is advantageous in that it realizes the stabilized permeable materials by a simple process. A combination of the properties of WRP and the reaction mechanisms of CAS leads to the permeable characteristics of the mixture. In other words, WRP, which itself is permeable, is immediately hardened by CAS upon watering, and CAS causes the mixture to have a low density in the early stage due to the expansion characteristics.

Compressive strength tests were carried out on the specimens after the permeable tests, as shown in Fig. 4.7. The strengths of the specimens after permeability testing were as high as those which were not subjected to permeability testing. Therefore, permeability history has little effect on the properties of the WRP-CAS mixtures. As the permeable period was about 1 hour in this series of experiments, it is important to evaluate the durability of the WRP mixtures under more severe conditions, such as cyclic drying-wetting or sulfate attacks, if they are to be used as construction materials such as roadbase.

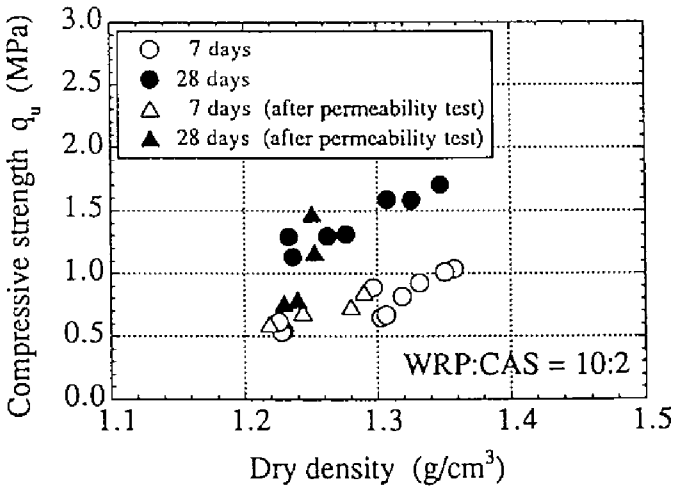


Fig. 4.7 Strengths before and after permeability test

(4) Applicability of WRP-CAS Mixtures

These test results show the effective utilization of WRP-CAS mixtures as construction materials. A method, in which WRP and CAS are poured into the site and then solidified by watering is a novel approach to soil stabilization. With the proper selection of strength and density for WRP and CAS, the mixtures can be utilized for various purposes; mixtures with a high density can be utilized as subbase course, while those with a low density can be used not only as subgrade and embankment materials, but also as well-drained materials such as permeable subgrade for roads and back filling for retaining walls, due to the characteristics of strength, shrinkage and permeability.

4.3.3 Basic Properties of Bagged WRP through Laboratory Studies

(1) Experimental Procedure

To evaluate the applicability of the Bagged WRP Method, a series of laboratory experiments were conducted. Non-Woven Fabric (NWF), 120 cm in length and 50 cm in width, was doubled, and the two layers were stitched together with a sewing machine. The NWF bags, 50 cm x 60 cm, were filled with 30 kg of premixed dry WRP-CAS, and the opened side was stitched so that the mixture could be closed up in the bag. The bags filled with the dry mixture were then laid flat and soaked in 1 m of either fresh or sea water in a closed cylindrical tank 1.5 m in diameter, as shown in Photo 4.1. Four bags were soaked in sea water, while five bags were soaked in fresh water. The mixtures were hardened by watering, as shown in Photo 4.2. They were salvaged and cut into 5 x 5 x 10 cm rectangular parallelepiped samples for unconfined compressive strength tests. Table 4.2 shows the curing conditions in these experiments.

(2) Selection of the Fabric for the Bags

The selection of the fabric must be based on the characteristics of NWF, such as filterability, tensile strength, and resistance. Three types of NWF, shown in Table 4.3, were preliminarily

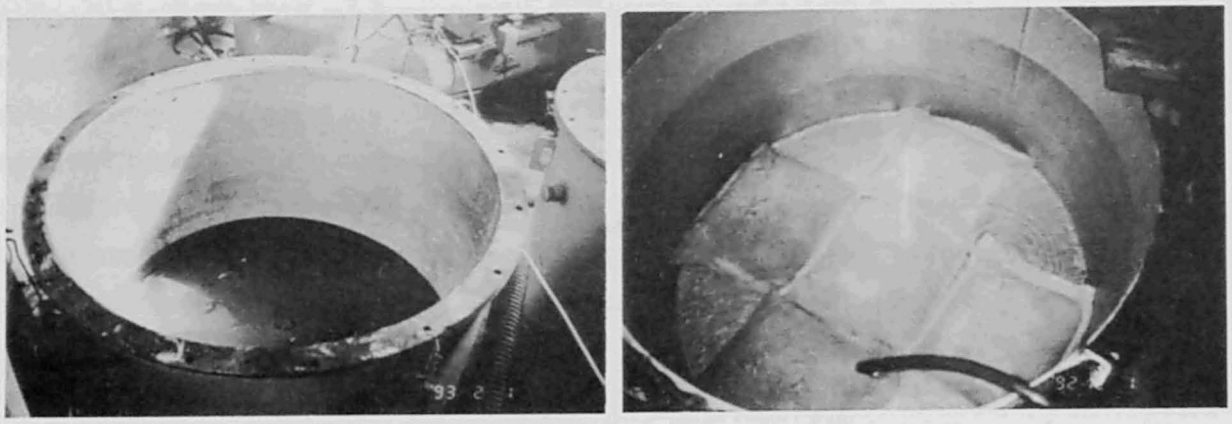
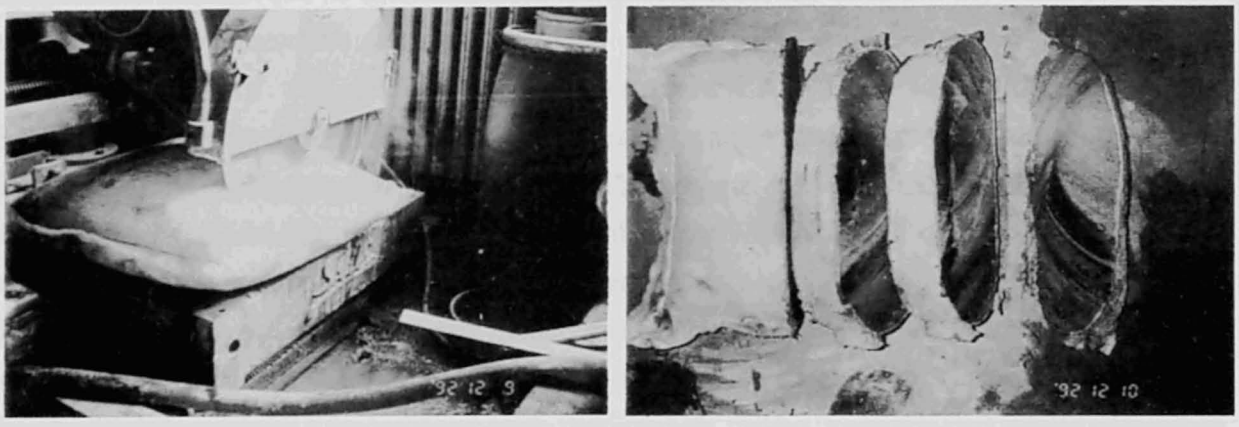


Photo 4.1 Curing of bagged WRP



(a) Cutting of bagged WRP (b) Cut samples

Photo 4.2 Hardened bagged WRP

Table 4.2 Curing conditions of the Bagged WRP Method

Mix proportions	WRP:CAS = 7:3, 8:2
Curing water	fresh water(tap water), sea water(artificial)
Curing temperature	14 - 20 ℃

Table 4.3 Characteristics of non-woven fabric

Type	SP	VN-160	VN-300
Mass (g/m^2)	80.0	160.0	300.0
Thickness (mm)	0.5	1.5	3.0
Tensile strength (kN/m)			
lengthwise	4.0	9.0	19.0
widthwise	3.0	7.0	15.4
Permeability (cm/s)	0.35	0.25	0.15
Open area size (mm)	0.05	0.07	0.05
Applicability	unsuitable	unsuitable	suitable

tested. Only one NWF, however, was selected for the following experiments due to its superior qualities. When using the geotextile "SP" (span-bond), the inner mixture issued forth from the open area of the NWF and the curing water became a little muddy. This is a problem when the method is applied at the field site. Both "VN-160" and "VN-300" functioned effectively as a separator and a protector, respectively, and the curing water was kept clean. The "VN-160" bag, however, was stretched out after carrying the mixture due to the heavy weight. "VN-300" was the most applicable bag because of its filterability and tensile characteristics.

(3) Hardening Characteristics of Bagged WRP

The WRP-CAS mixtures were hardened effectively by the expansion of CAS and the restriction of the fabric. The mixtures were poured into the fabric bags and became hardened immediately upon watering; that is, the mixture salvaged after watering for 2-3 minutes behaved as one hardened block rather than as a flexible clod. Figures 4.8 and 4.9 show the strengths of the WRP-CAS mixtures sampled from the NWF bags. There is a strong correlation between the dry density and the compressive strength as well as the samples from the laboratory tests, and the regression plots are considered to be in the same range as those of the laboratory test samples. However, the Bagged WRP Method samples have lower strengths and lower densities than the laboratory samples, because the former mixtures are free to expand as long as the fabric bags stretch while the later are restricted by the rigid mold. The strengths of WRP:CAS = 8:2 mixtures cured in sea water are much lower (about 100 kPa) than the strengths of any other mixtures because of the looseness of the filling in the bag. It is important, therefore, that the CAS expands and the fabric provide resistance to compensate for the incomplete filling. The other mixtures had a stress of at least 200 kPa and usually had a strength higher than 500 kPa after 28 days, which exhibits a sufficient hardening effect.

Figure 4.10 illustrates the density and the water content of the mixtures by molding tests and bagged WRP tests. The regression plot is expressed by

$$\rho_d = 1.860 - 0.0163w \quad (R = 0.884)\,. \qquad \text{(Eq. 4.2)}$$

This equation is almost the same as that for the molding tests; therefore, the basic properties of the mixtures by the Bagged WRP Method are similar to the later ones, and an estimation of strength is possible by the above-mentioned process.

The hardening reaction occurs gradually from the surface to the center of the mixtures because of water seepage. Figure 4.11 illustrates the relationship between the density and the water content of the three parts separated in the bag, that is, the upper and the lower parts are near the fabric and the center part is far from the fabric. The center has a higher dry density than the upper and the lower parts because the outer mixtures react immediately upon watering, expand, and compress the inner mixtures. It is thought that a decrease in permeability of the outer mixture, due to hardening, might prevent the water from reaching the inner mixture. Also

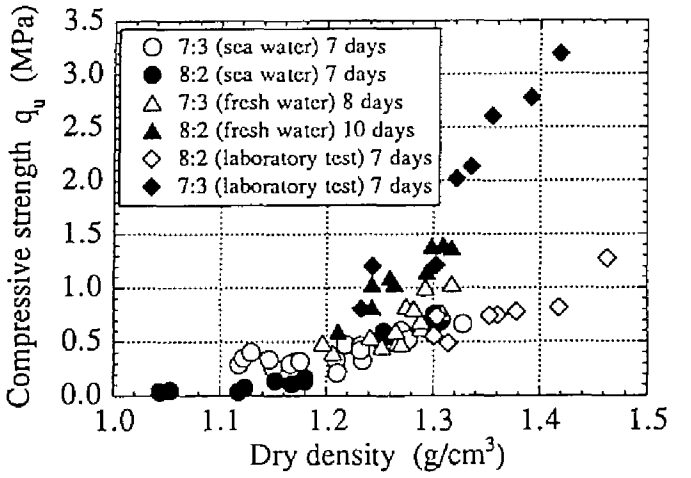


Fig. 4.8 Strengths of WRP-CAS mixtures by the Bagged WRP Method and laboratory tests

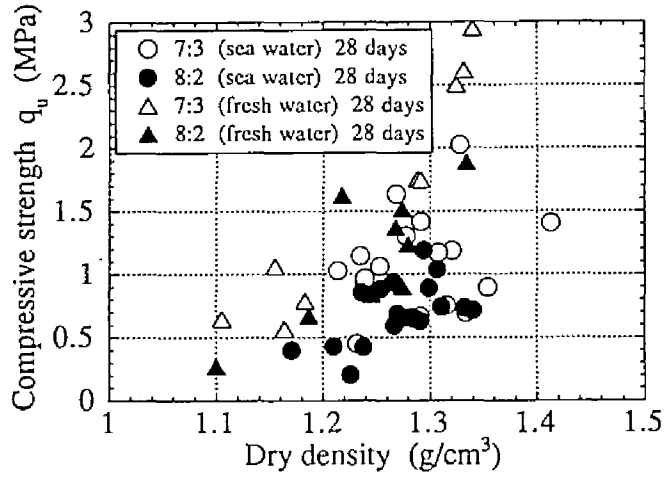


Fig. 4.9 Strengths of WRP-CAS mixtures by the Bagged WRP Method

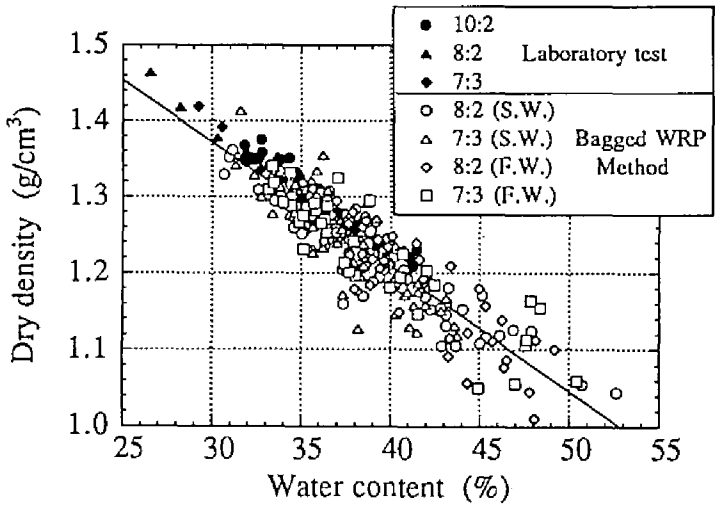


Fig. 4.10 Dry density versus water content of WRP-CAS mixtures by laboratory tests and the Bagged WRP Method.

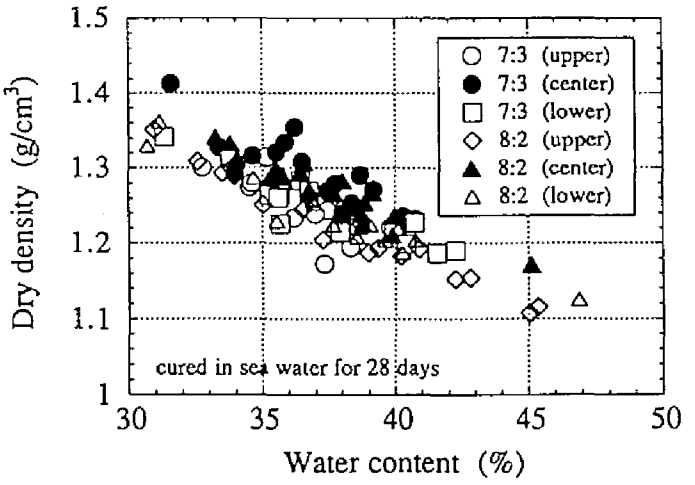


Fig. 4.11 Relationship between dry density and water content

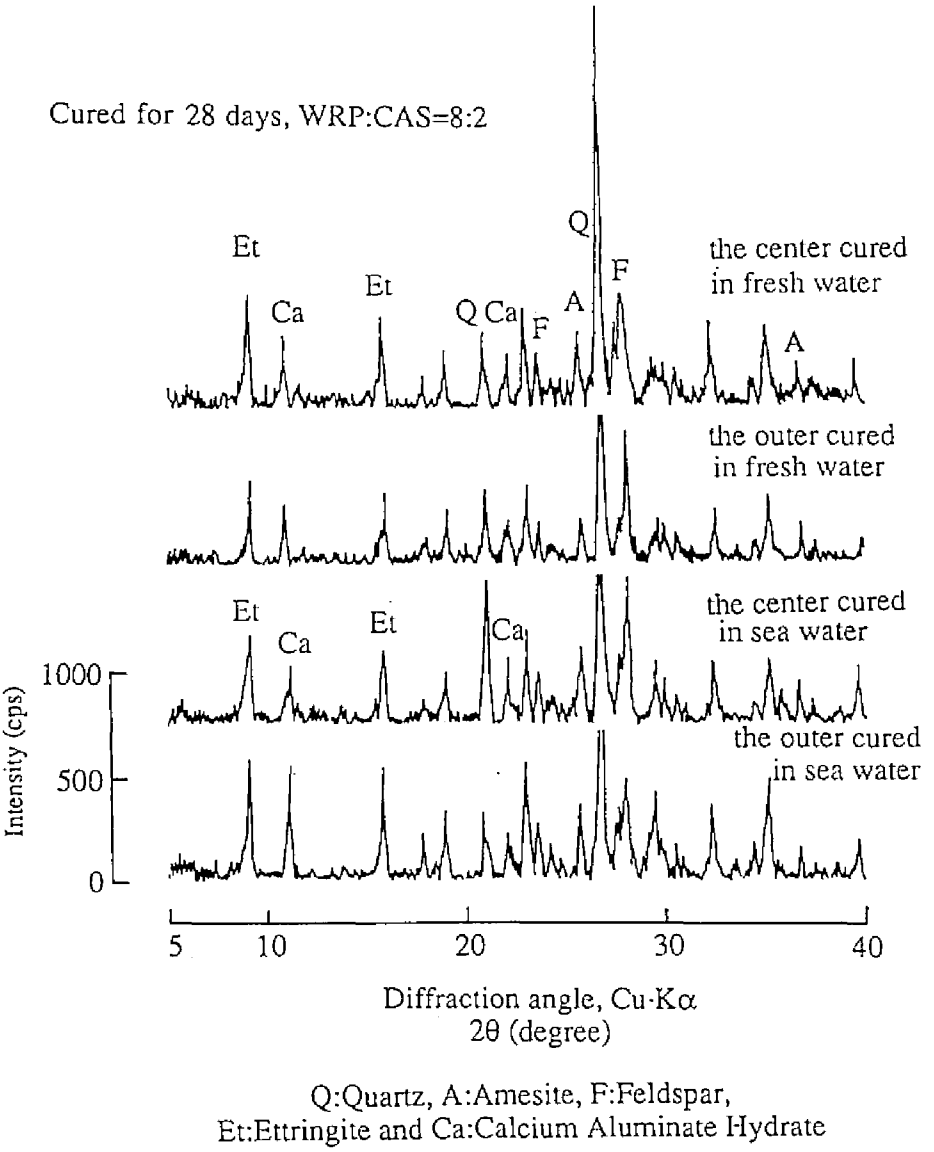


Fig. 4.12 XRD patterns for WRP-CAS mixtures

the effect of size must be evaluated to utilize this method at the site. According to the results of X-ray diffraction analyses on the mixtures (Fig. 4.12), ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) and calcium aluminate hydrate($4CaO \cdot Al_2O_3 \cdot 13H_2O$) are thought to contribute to the strength development because of the presence of Al and SO_4 in CAS. These hydrates react with a large amount of pore water, expand, and harden. The curing conditions and sampling positions hardly affected the X-ray diffraction patterns.

The mixtures soaked and cured in (artificial) sea water have much lower strengths than those cured in fresh water, as shown in Figs. 4.8 and 4.9. There are several possible reasons for this phenomenon. Since these tests were carried out in different seasons, a 2-5℃ difference in curing temperature might lead to the variance in strengths. And of course, the variety of WRP properties can not be ignored. The main reason for this difference, however, can be the composition of sea water, namely, 0.2% SO_4^{2-} of and 1.5% Cl^- which might affect the hardening reaction, and Mg^{2+} is considered to generate the ion exchange function of Ca^{2+}. The durability of hardened materials in sea water is also important. It is well known that $MgSO_4$ in sea water can destroy cement bonds and produce such expansive materials as ettringite. The durability of the hardened materials in sea water, however, is not discussed in detail in this study, because the main phenomenon, the formation of ettringite, is advantageous to the development of strength of the WRP stabilization using CAS.

(4) pH Characteristics of Cured Water

It is suspected that a composition of sea water might prevent an increase in pH, and consequently, inactivate the hardening reaction, as shown in Fig. 4.13 which illustrates the pH values of curing water. The low pH value is agreeable from an environmental viewpoint. The pH value of sea water in which the WRP-CAS bags were cured is lower than 9.0, satisfying the Japanese environmental standards for sea water. In the case of curing in fresh water, however,

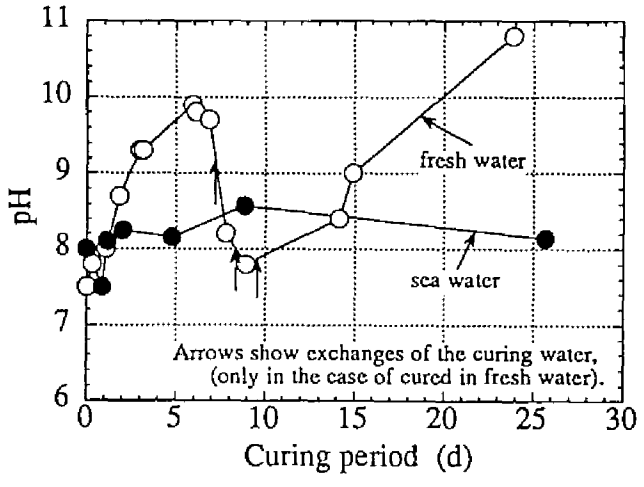


Fig. 4.13 pH values in tanks where the mixtures were cured

the pH values increased due to curing in spite of the water exchanges.

Figure 4.14 shows the results, for tests in which 1 kg dry mixtures were poured into small bags and soaked in fresh water or sea water. The cured sea water remained neutral in its pH value regardless of the ratio of the water and the mixture. Cured in fresh water, the pH exhibited alkaline and was dependent upon the amount of water. If the fresh water was changed every 3 days, the pH value decreased to a neutral level (below 9.0) after about 1 week, as shown in Fig. 4.15. Therefore, the Bagged WRP Method is applicable in open areas but not in closed areas, even in the case of curing in fresh water.

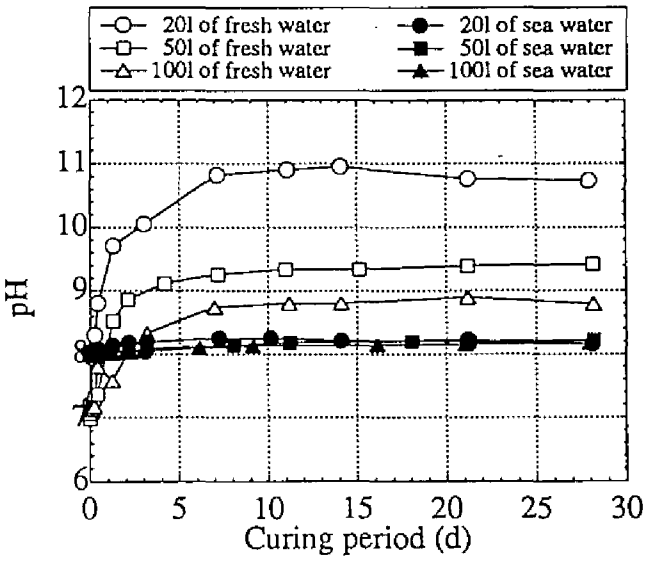


Fig. 4.14 pH changes of curing water for WRP mixtures

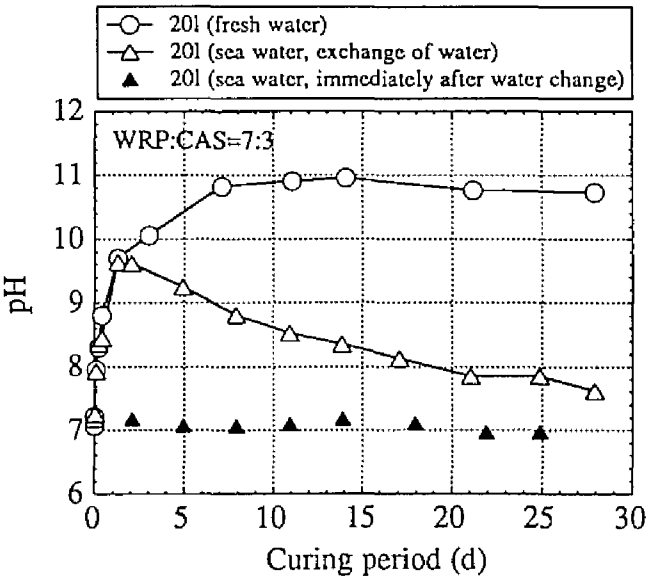


Fig. 4.15 pH changes of curing water for WRP mixtures

4.3.4 Field Test of Bagged WRP Method

(1) Test Description

The field test was conducted to evaluate the applicability of bagged WRP. Two types of fabric bags made of woven and non-woven fabrics (Table 4.4), with a volume of about 0.7 m^3, were used for the field test. WRP and CAS were mixed under dry conditions at a ratio of 8 : 2, and each fabric bag was filled with 1.0 Mg of the mixture, as shown in Fig. 4.16. The test was conducted on a sea bed which consisted of sedimented sand and clay soil. The site was the corner of a quaywall in a harbor area and the bags were set on the sea bed using a track crane located on land, as described in Figs. 4.17 and 4.18. Photo 4.3 shows the state of the field test.

(2) Hardening Characteristics of Bagged WRP

Thirty-six days after construction, the bags were salvaged and specimens for the strength test were sampled, as shown in Fig. 4.16, from the mixtures in 8 bags. The weight of the bagged WRP changed to 1.2-1.3 Mg due to watering.

An unconfined compressive strength test was performed 45 days after construction. Figure 4.19 shows the strength and density values of the mixtures. Both strength and density showed

Table 4.4 Properties of the fabrics of the bags used in the field test

Type	Non-woven fabric	Woven fabric
Material	Polyestel	Polypropylene
Mass (g/m^2)	300	-
Thickness (mm)	3.0	-
Tensile strength (kN/m)		
lengthwise	18.6	44.1
widthwise	15.1	42.9

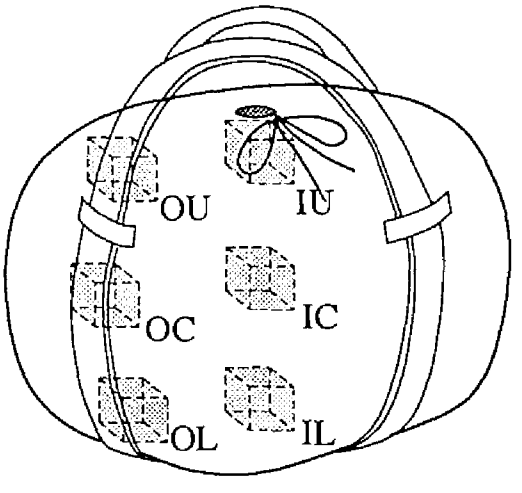


Fig. 4.16 Description of bag and sample locations

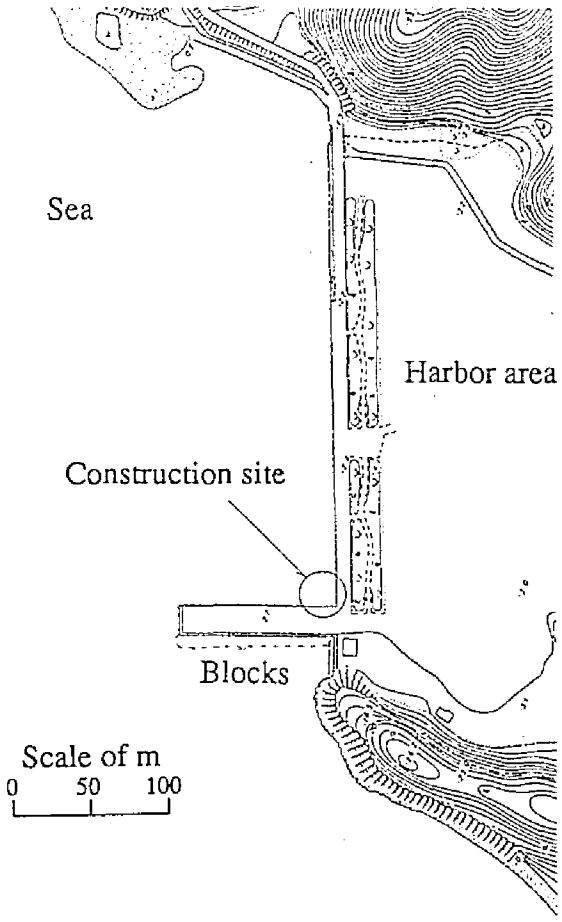


Fig. 4.17 Location of the field test site

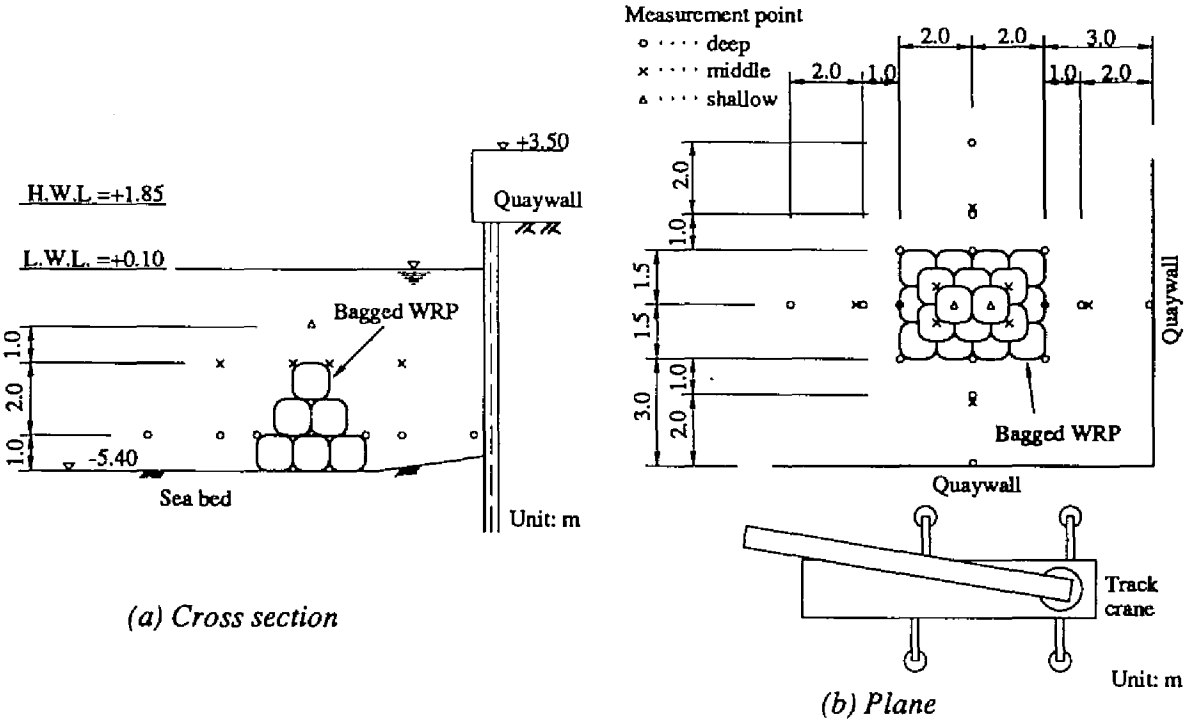


Fig. 4.18 Description of the field test site

(a) Mixing of WRP and CAS

(b) Bag filled with WRP-CAS mixture

(c) Soaking of bagged WRP

(d) Salvaging of bagged WRP cured in the sea

(e) WRP-CAS mixture hardened in the bag

Photo 4.3 Field test of Bagged WRP Method

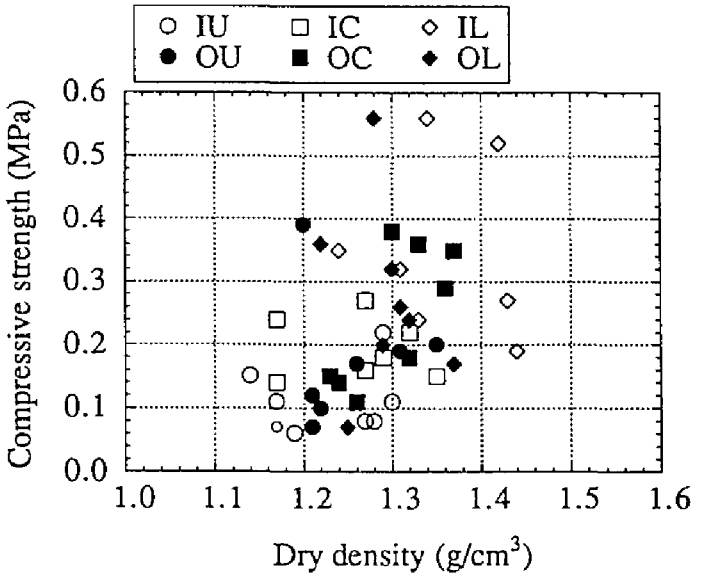


Fig. 4.19 Strength characteristics of the bagged WRP mixtures

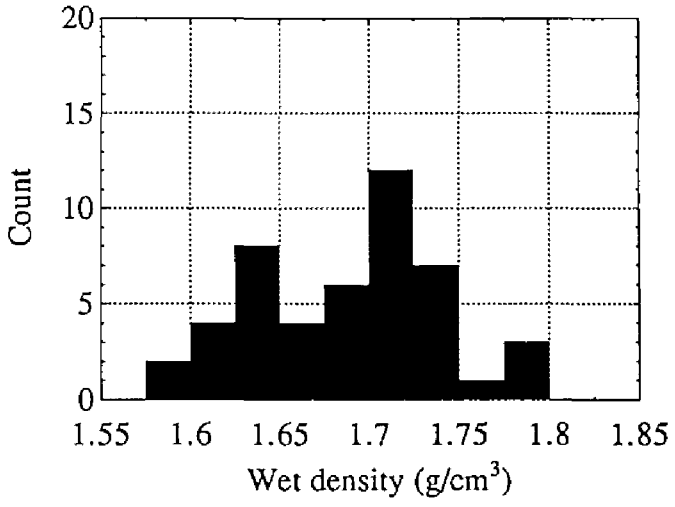


Fig. 4.20 Wet density of the bagged WRP mixtures

wide variations; strength was in the range of 50-600 kPa and density was between 1.15-1.45 g/cm^3. The strength and density characteristics were influenced not by the disposition of the bags or the type of fabric used, but were dependent on the position of the sample within the bag. The mixtures at lower positions in the bag showed higher strengths and densities, probably as a result of the expansive phenomenon of CAS which advances gradually by watering. The densities were almost equivalent to those measured in the laboratory using 30 kg of bagged WRP (1.10-1.45 g/cm^3), as stated in Section 4.3.3. The strengths, however, were lower than those in the laboratory tests (0.2-2.0 MPa). The lowest strength, however, was still above 50 kPa, and even the mixtures located at the center of the bag, exhibited a hardening effect due to both the hydrating characteristics of CAS and the permeability of WRP.

Figure 4.20 indicates the distribution of wet density, which was in the range of 1.60-1.80 g/cm^3. Assuming that the degree of saturation is 100%, the density of the solid phase is calculated to be 2.1-2.3 g/cm^3, which is lower than the particle density of WRP (2.65 g/cm^3). The hardening and expansive reactions of CAS are considered to form light-weight reactive products such as ettringite.

Thus, both the light-weight and the strength development characteristics of the bagged WRP were determined through field scale performances as well as laboratory experiments.

(3) Environmental Impact

After setting the fabric bags on the sea bed, fabrics functioned effectively as separators and protectors, and there was no pollution of the sea water due to the WRP. No remarkable deformation to either sea bed or bagged WRP occurred.

The water quality was measured at the points illustrated in Figs. 4.18. Change in the pH value are shown in Fig. 4.21. CAS itself has a high pH level and that of the sea water showed a gradual but very slight increase from the time the bagged WRP was set. It was lower than 9.0, satisfying the environmental standards set down by law in Japan. These results agree with those

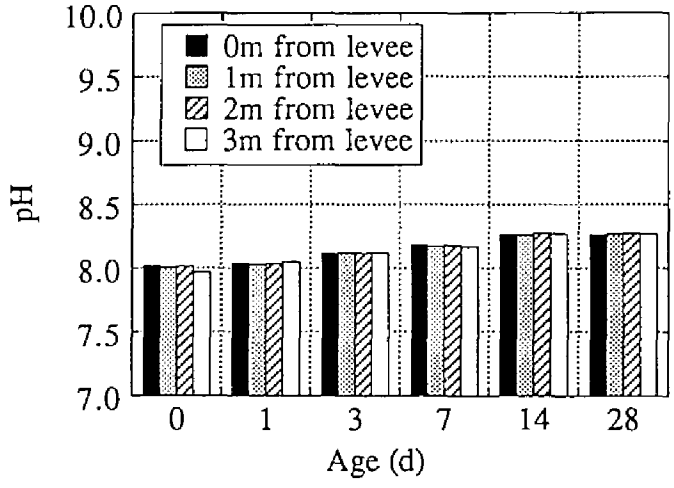


Fig. 4.21 pH changes around bagged WRP levee

Table 4.5 Changes in water quality with application of the Bagged WRP Method

Curing day	0[1)]	0[2)]	1	3	7	14	28
Date	6/21	6/21	6/22	6/24	6/28	7/5	7/19
Temperature (℃)	20.4	20.3	20.5	20.8	21.4	23.2	24.4
Salt concentration (%)	3.36	3.30	3.35	3.36	3.43	3.34	3.37
pH	7.90	8.01	8.04	8.12	8.18	8.27	8.27
Conductivity (mS/cm)	51.1	50.3	50.9	51.1	52.0	50.6	51.1
Dissolved oxygen (mg/l)	-	7.00	6.66	7.03	7.29	7.15	6.77

1) Before bagged WRP were set on the sea bed
2) After bagged WRP were set.

in the laboratory studies stated in Section 4.3.3. It is suspected that the composition of sea water might prevent the increase in pH by functioning as a buffer. The pH value shown in Fig. 4.21, and other measured values did not depend on the distance from the bagged WRP.

Table 4.5 lists the changes in measured values for the water quality. The salt concentration retained the value measured before the bagged WRP was set. A rise in water temperature was observed and was thought to be caused by the normal seasonal weather changes. Neither dissolved oxygen nor conductivity were influenced by the soaking of the bagged WRP.

In conclusion, no remarkable changes in the quality of the sea water were recognized in terms of environmental impact.

4.3.5 Material Functions of the Bagged WRP Method

The functions of the materials used, namely, WRP, CAS, and fabric bags, were summarized through experimental studies and are shown in Fig. 4.22. The permeability of WRP, the expansion of CAS, the reactive mechanisms of CAS (and WRP), and the function as a separator, a protector, a filter, and a fluid transmission of the fabric are combined effectively in this method. Consequently, the bagged WRP exhibits high strength, light weight and a low pH value for the cured water.

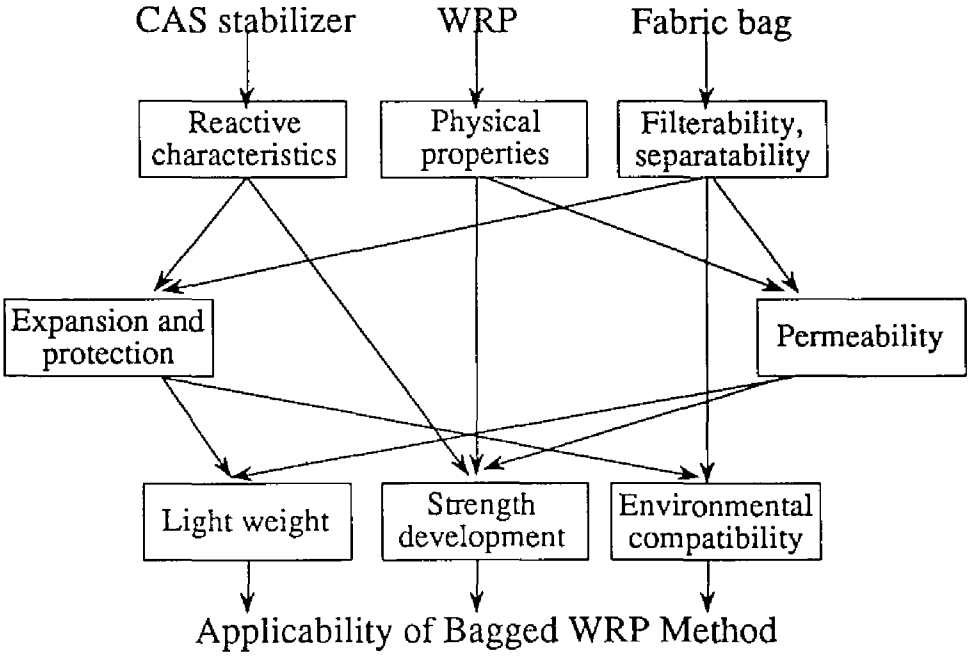


Fig. 4.22 Relationship of material function used in the Bagged WRP Method.

4.4 Applicability Evaluation of Bagged WRP by an Analytical Approach

4.4.1 Applicability of the Bagged WRP Method

The Bagged WRP Method is applicable to sunken levee materials as a substitute for rubble or concrete blocks, or for seafloor ground improvement. An application of the Bagged WRP Method to tidal flat construction was illustrated in Fig. 4.1.

Steps for construction of the man-made tidal flats and related geotechnical problems are summarized in Fig. 4.23. There are some geotechnical problems in tidal flat construction, the most important of which can be problems on the ground and levee stability in the sunken-levee construction. The construction of these man-made tidal flats uses a sunken levee to retain the soil materials of the tidal flats, and ground improvement work for sunken-levee stability is necessary because the materials ordinarily used for sunken levee, such as rubble or concrete blocks, are very heavy (density of about 2.6 g/cm^3).

The Bagged WRP Method has some advantages when it is applied to a sunken levee. The materials made by this method are light weight (density of about 1.5-1.7 g/cm^3); therefore, even a soft seafloor ground does not require any soil improvement. Due to the deformation of inner

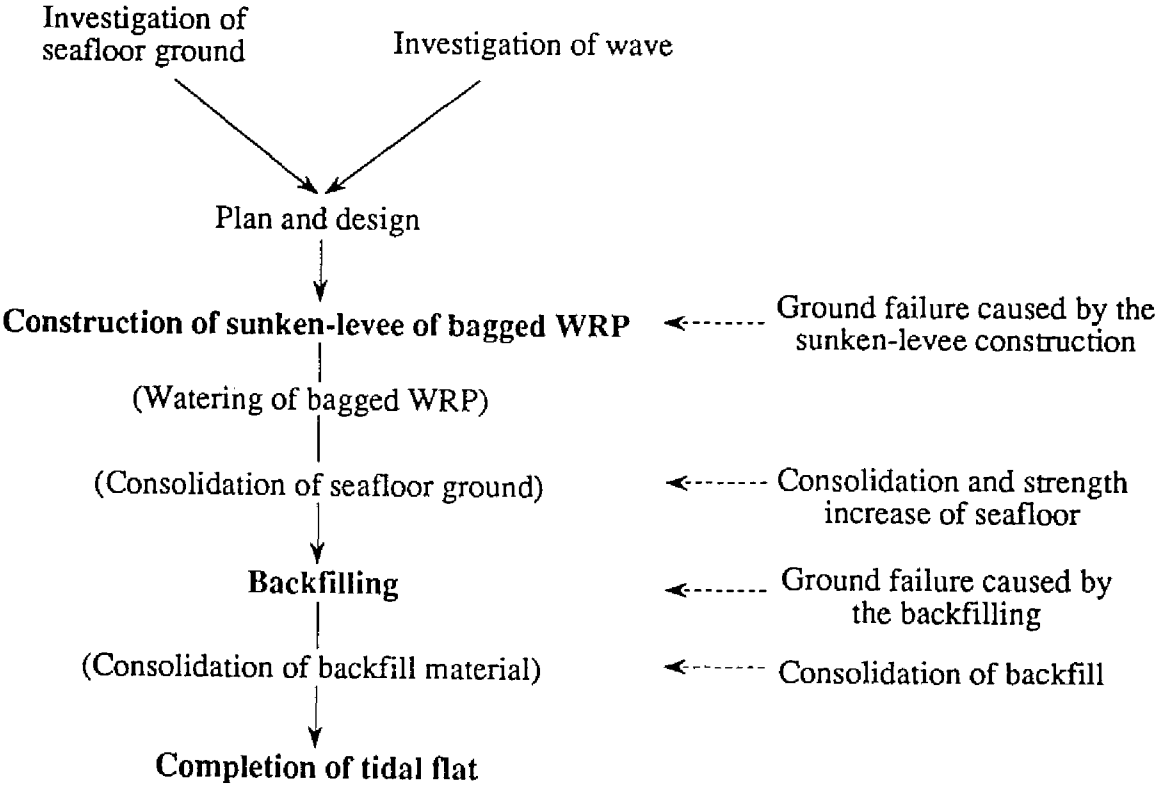


Fig. 4.23 Construction steps of sunken-levee of bagged WRP and tidal flats and associated possible geotechnical problems

mixtures until they harden, the bags can adhere to each other. Of course, one of the most attractive merits is waste utilization as a substitute for natural rubble.

4.4.2 Stability Analysis of Sunken-Levee Construction by Bagged WRP

(1) Conditions of Analysis

The Bagged WRP Method is considered to be advantageous for sunken-levee construction because the hardened mixtures are much lighter in weight than the materials ordinarily used, such as ripraps or concrete blocks. A stability analysis of the sunken levee construction was performed to clarify the applicability and the design concept of bagged WRP under the conditions of the sea bed.

A conceptual model is described in Fig. 4.24. The gradient and the cohesion of the sea bed, which is assumed to be a clay soil ground, are parametric. The safety factor (F_s) is calculated by the following equation according to the circular arc method:

$$F_s = r\,\Sigma cL \,/\, \Sigma(W+P)a \qquad \text{(Eq. 4.3)}$$

where r and L are the radius and the arc length of the circular slip surface (m), respectively, W is the weight of the sliced ground (N), and a is the arm length of the sliced ground (m). The mutual friction of bagged WRP is ignored and the load on the sea bed by bagged WRP, P (kPa), is taken into account. The cohesion of the sea bed ground, c (kPa), is as follows:

$$c = k\,(\rho_{sat} - \rho_w)\,g_n\,z + c_{surf} \qquad \text{(Eq. 4.4)}$$

where ρ_{sat} and ρ_w are the bulk density of the ground and of the water, respectively (g/cm^3), z is the depth of the ground, g_n is the gravitational acceleration, c_{surf} is the cohesion of the ground

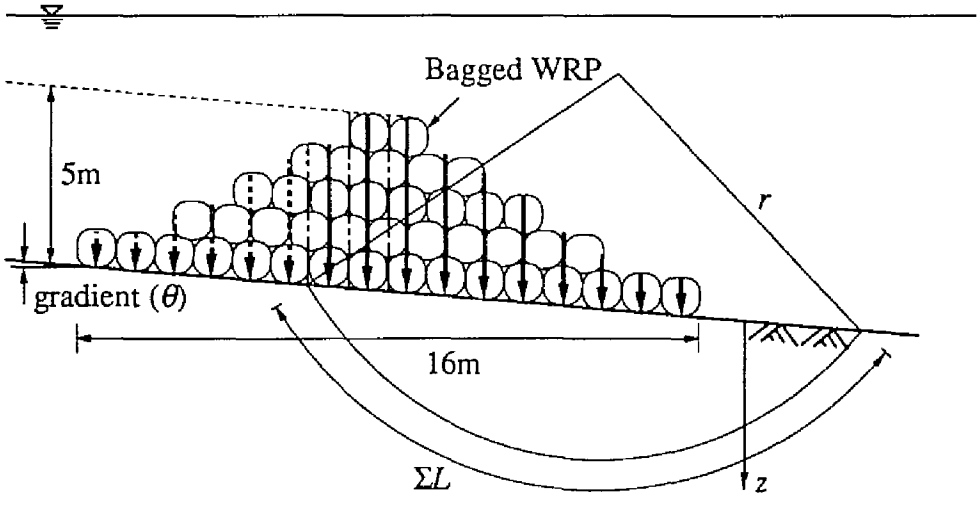


Fig. 4.24 Cross section for the stability analysis

Table 4.6 Conditions for stability analysis

Sunken-levee	
Density of bagged WRP (g/cm^3)	1.70
Density of riprap (g/cm^3)	2.60
Sea bed	
Density, r_{sat} (g/cm^3)	1.40
Gradient of the surface (degree)	0 - 10
Cohesion of the surface, c_{surf} (kPa)	0 - 10

surface, and the rate of strength increase, k, is assumed to be 0.33. The conditions for the analysis are shown in Table 4.6.

(2) Results and Discussions

Figure 4.25 shows the safety factors under various gradient and sea bed cohesion conditions. The representatives of the sliding surface are shown in Fig. 4.26. When the c_{surf} value is very small, the sliding surface exists in the very shallow ground. This indicates that the presented failure surface exhibits only the settlement, and consequently, becomes a trigger of the post failure.

When a safety factor of 1.2 is assumed as the required condition for design, the sea bed and the bagged WRP are considered to be stable when the cohesion of c_{surf} is higher than 7.5 kPa. Even when c_{surf} is 5 kPa, a safety factor of 1.2 is achieved if the ground gradient is less than 5 degrees. Using ripraps whose density is 2.6 g/cm^3 as the sunken-levee material, the safety factor is below 1.0 even when the c_{surf} value is 10 kPa. This indicates the need for sea bed improvement. The Bagged WRP Method is not only effective for sunken-levee construction,

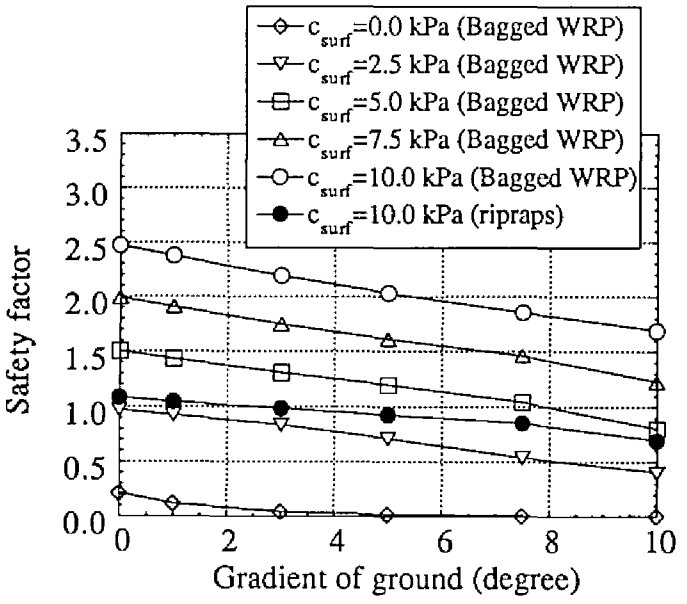
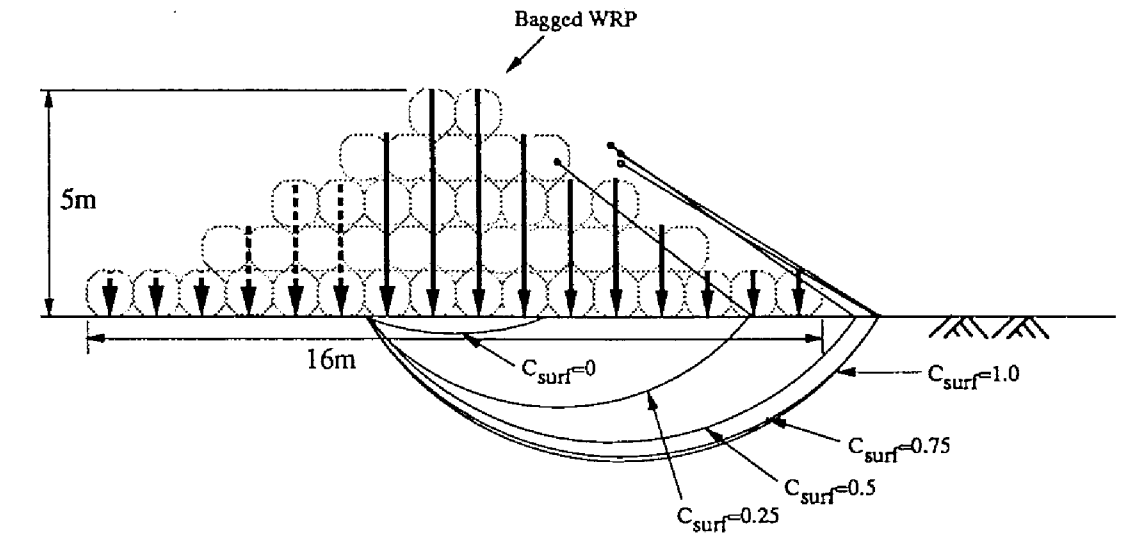
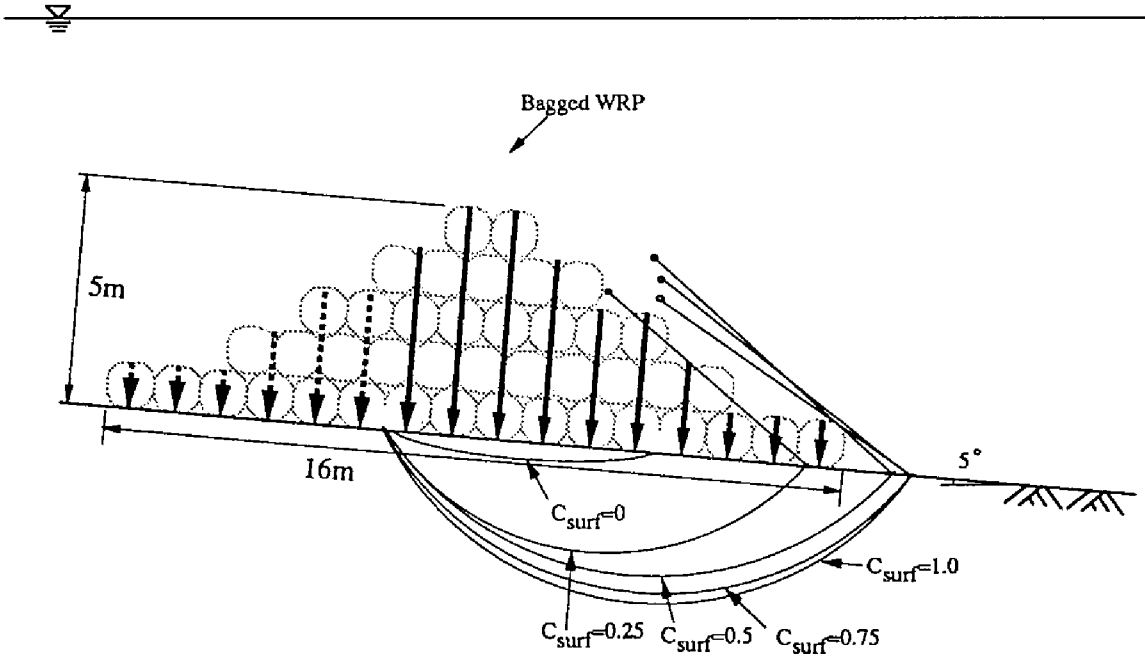


Fig. 4.25 Results of the stability analysis of the sunken-levee slope



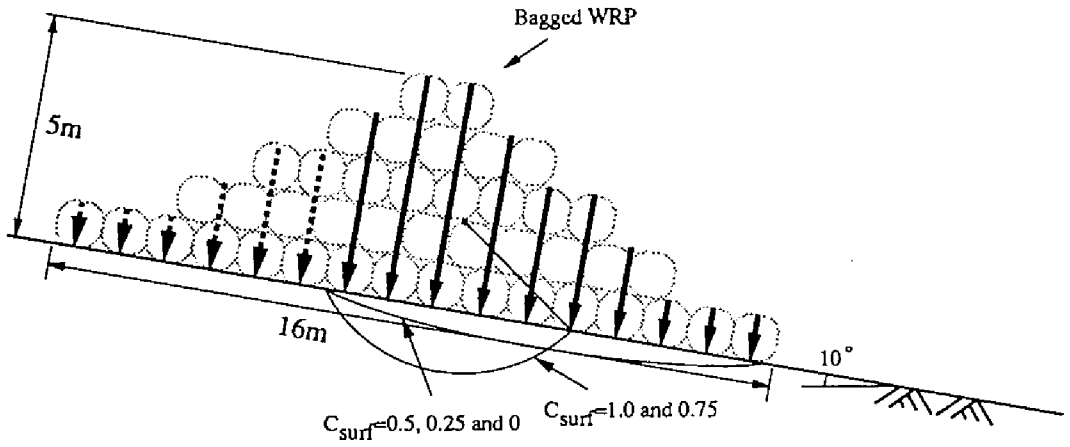
(a) 0 degree gradient

Fig. 4.26 Sliding surface obtained from the stability analysis



(b) 5 degree gradient

Fig. 4.26 Sliding surface obtained from the stability analysis



(c) 10 degree gradient

Fig. 4.26 Sliding surface obtained from the stability analysis

but also extends the applicability of the sunken-levee construction itself.

Sunken levees constructed with bagged WRP are advantageous in that the back area of the levees will be filled with sedimenting dredged clay materials or can be utilized as a reclamation area for surplus soil or other by-products. Consequently, tidal flats can be formed, as shown in Fig. 4.1. In this study, however, the long term stability of sunken-levees and the influence of the reclamation of dredges, surplus soil, or other materials for tidal flats are not discussed. Only the short term stability of a sea bed loaded with bagged WRP is discussed. The short term stability can be much more important than the long term stability. And, if it is cleared, the consolidation behavior of the seafloor ground will lead to strength development and higher stability. The influence of reclamation is thought to be negligible when compared with the influence of sunken-levee construction, because the density of reclaimed materials is comparatively low.

4.5 Conclusions

A new method, called the Bagged WRP Method, is proposed for the potential utilization of waste rock powder (WRP) as a construction material. WRP is a by-product discharged from rock crushing plants, and its application as a construction material is required for use in large quantities. The Bagged WRP Method, whereby fabric bags are filled with a dry WRP-CAS

mixture and solidified by soaking, depends on the characteristics of the WRP itself, the hardening materials of the Carbonated-Aluminate Salt (CAS) and the fabric of the bags. The following conclusions were obtained in this chapter:

(1) WRP-CAS mixtures have a highly solidified strength, low density, and high permeability, due to the reactive characteristics of CAS and the basic properties of WRP. As far as the application of WRP-CAS mixtures is concerned, they can be applied not only as subbase or embankment materials but also as well-drained materials such as permeable subgrade for roads or back-filling for retaining walls.

(2) The basic properties of bagged WRP-CAS mixtures were evaluated through an experimental study. The hardening reaction proceeds immediately after soaking and high strengths are obtained. The relationships between density and strength are similar to those of the WRP-CAS mixtures which are hardened but not bagged.

(3) Field tests evaluated the applicability of the Bagged WRP Method. The method can be conducted with traditional equipment. The inner mixtures of bagged WRP are both light in weight and high in strength even when cured in a sea environment which has a compressive strength of 50-600 kPa and a wet density of 1.6-1.8 g/cm^3.

(4) The sea water in which the bagged WRP is soaked exhibits a pH value below 9.0. No remarkable changes in the sea water quality, from the viewpoint of environment impact (e.g. in pH), were observed during the execution or curing of the Bagged WRP Method.

(5) The stability analysis clarified that bagged WRP is more advantageous to sunken-levee construction than rock or concrete blocks because of its light weight, and ground improvement work of the sea bed is not needed. This means that the Bagged WRP Method is not only effective for sunken-levee applications, but also can extends the applicability of levee construction itself to various areas under various conditions.

(6) To minimize environmental damage and attain sustainable development, the construction of man-made tidal flats is required as a substitute for the tidal flats which will disappear due to reclamation or dredging works. Sunken-levee construction is required to retain soil materials in tidal flats. The Bagged WRP Method represents a useful new strategy for both waste management and environmental mitigation.

References for Chapter 4

Committee on the waterfront development by LANDFILL, JSCE (1995). *Concept for LANDFILL island*, 263p.

Fukuda, K., T. Kokura, T. Inoue and H. Hanehara (1992). "Construction project of man-made tidal flats for environmental mitigation," *Proc. Symp. Development of Waterfront Areas*, pp.33-38 (in Japanese).

Hamasuna, J. (1992). "Man-made tidal flat by using waste materials," Treatment and Recycling Technology and Utilization of Waste Materials, Kogyo-Gijutsu-Kai, pp.548-559.

Kamon M., and T. Katsumi (1994). "Potential utilization of waste rock powder," *Proc. 1st Inter. Cong. Environmental Geotechnics,* pp.287-292.

Kamon M., and T. Katsumi (1995). "New strategy for potential waste utilization as geo-materials," *Proc. 11th Eur. Conf. Soil Mech. Fndn. Eng.,* Vol.2, pp.61-66.

Kuno, G., M. Yoshihara, H. Ishizaki and Y. Omodaka (1992). "Properties of improved surplus soil by liquefied soil stabilization method," *Proc. 37th Symp. SMFE,* JSSMFE, pp.1-6 (in Japanese).

Mehta, P.K. (1976). "Mechanism of expansion associated with ettringite formation," *Cement & Concrete Res.,* Vol.3, pp.1-6.

Miki, H., Y. Hayashi and N. Aoyama (1992). "Development of new techniques to heighten the value of soil materials," *Civil Engrg. Jour.,* PWRI, Ministry of Construction, Vol.34, No.11, pp.58-65 (in Japanese).

Nishida, K., S. Sasaki and Y. Kuboi (1992). "Utilization of waste rock powder for the lime stabilization of residual soil," *Soil Improvement,* CJMR Vol.9, Elsevier Appl. Sci., pp.55-70.

Pradhan, T.B.S., Y. Hirano, T. Tanabe and H. Natori (1995). "Stabilized light soil using vinylidene chloride form," *Proc. 11th Eur. Conf. Soil Mech. Fndn. Eng.,* Vol.2, pp.121-126.

CHAPTER 5

Environmental Influence of Geotechnical Waste Utilization and its Control

5.1 General Remarks

Environmental compatibility has to be taken into account when wastes or by-products are reused as earthen materials such as embankments or subgrade. One serious case is thought to be caused by the leachate of hazardous components, such as heavy metals or other toxic chemicals. Therefore, the leachate mechanisms have been researched in terms of the promotion of waste utilization in recent years by some researchers (e.g., Bialucha et al 1994; Fällman and Hartlen 1994). Under the present legal system on waste management, the materials which contain these hazardous chemicals are actually difficult to utilize as construction materials or to put in the geoenvironment as they are. Environmental influences due to alkaline leachate from stabilized waste also cause severe problems. An alkali migration will increasingly become a much more serious environmental concern because the alkali exists extensively. At present, some kinds of waste materials have been recommended for chemical stabilization by cement or lime in order to improve their properties for utilization purposes, as stated in Chapters 2 and 3. In particular, surplus soils and waste sludge, which are by-products originating from the ground, are expected to be used with cement or lime stabilization in larger quantities.

About 437 million m^3 of surplus soil and 15 million tons of waste slurry were generated from construction works in fiscal 1993, and more than 50% and 92% of them, respectively, were disposed of in landfill sites instead of being reused. The recycling of other construction by-products, such as waste concrete and waste concrete-asphalt, increased markedly (48% to 67% and 58% to 78%, respectively, from 1990 to 1993), according to an investigation by the Ministry of Construction (1995). Therefore, the utilization of surplus soils and waste sludge for geotechnical purposes is greatly needed. To promote the effective use of surplus soils, their properties must sometimes be improved by cement and/or lime stabilization. In the "Technical Manual for Recycling of Surplus Soil," established by the Ministry of Construction in 1994,

Table 5.1 Classification of surplus soil

Class	Content	Use
1st class soil	Sand, gravel, and the corresponding	- Back filling for construction work - Back-fill for structure - Road embankment - Fill for building lot
2nd class soil	Sandy soil, gravelly soil, and the corresponding	- Back-fill for structure - Road embankment - River dike - Fill for building lot
3rd class soil	Clay soil which can be executed on, and the corresponding	- Back-fill for structure - Road subgrade embankment - River dike - Fill for building lot - Water area reclamation
4th class soil	Clay soil, except for 3rd-class soil	- Reclamation in coastal area
Sludge	Waste sludge/slurry	- No use

these materials are divided into 5 classes, according to quality, as shown in Table 5.1. Their utilization purposes are clearly introduced for each class of soil in order to promote recycling. Soil stabilization methods, such as cement or lime hardening, are also recommended for recycling purposes.

As materials stabilized by cement or lime exhibit a high pH value, the environmental impact of alkaline migration must be carefully considered. The mechanisms of alkaline migration and the methodology of its control in the soil have not been discussed sufficiently from the standpoint of surplus soil utilization. The Technical Manual for Recycling of Surplus Soil does not mention these problems clearly and some local governments do not accept the utilization of such chemically stabilized soils because of their alkaline leachate. At present, concepts for the assessment and control of environmental influences caused by stabilized soils should be accomplished for the purpose of geotechnical waste utilization.

The importance of the conduction phenomenon in soils has recently been emphasized (e.g., Mitchell 1992). In particular, several researchers such as Shackelford and Daniel (1991) and Yong et al. (1992) summarized the migration mechanisms of contaminants in soil to prevent and/or control the contamination of the ground. From the viewpoint of environmental compatibility in geotechnical waste utilization, the environmental impact of alkaline leachate as well as harmful substances must be addressed. To encourage the recycling of the by-products of surplus soils, alkaline leachate migration mechanisms from stabilized soils have been studied (e.g., Amano et al. 1980; Kitsugi 1989; Mishima et al. 1994) and clayey soil was found to be a filtration cover for stabilized soil to minimize alkaline migration by its high alkaline buffer ability (Miki et al. 1994; Sano et al. 1993). However, clayey soils are not always considered to be

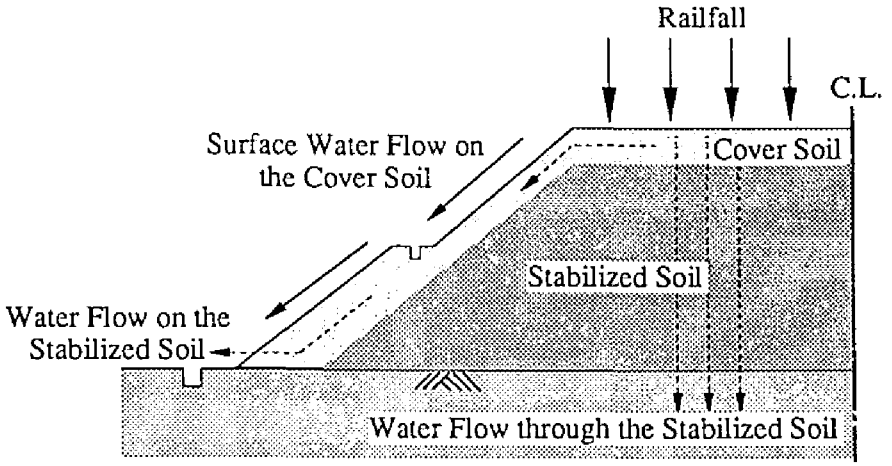


Fig. 5.1 Water flow around the embankment using stabilized soil

suitable for a cover because it is difficult to construct a compacted layer with clay. Besides, alkaline migration and its control by stabilized materials is strongly affected not only by the individual properties of the stabilized layer and the filter cover, but also by a combination of these properties. The latter influences have not yet been sufficiently discussed. Figure 5.1 shows a typical cross section of an example of geotechnical waste utilization, an application of stabilized surplus soil to an embankment.

In this chapter, the methodology to control the environmental impact induced by the application of cement stabilized soil is discussed. The mechanisms of alkaline leachate from the stabilized soil and the neutralization ability of the soil for a cover or filtration layer will be discussed, and the design concept for alkaline migration control will be proposed. The fundamentals of alkaline migration due to chemically stabilized soil are summarized based on the literature review in Section 5.2. The alkaline migration of stabilized soil and its control by a filtration layer will be discussed through the experimental study in Section 5.3. Based on the test results, in Section 5.4, the minimum thickness for a filtration layer of a stabilized-soil embankment was estimated through a parametric analysis for the example shown in Fig. 5.1.

5.2 Background

5.2.1 Calcium Alkali-Soil Interaction

Leachate ions existing in soil-water systems have a tendency to be adsorbed on the surface of clay particles due to electric gravitation. The gravitational strength depends on the species of ion. Multiply charged ions have a larger gravitational strength and the order is as follows;

$$Li^+ < Na^+ < H^+ < K^+ < NH_4^+ << Mg^{2+} < Ca^{2+} << Al^{3+} \qquad \text{(Eq. 5.1)}$$

Typical ions in untreated and stabilized soils are Na^+ and Ca^{2+}. The order of gravitational strength means that calcium alkali has different characteristics from sodium alkaline. Sodium hydroxide (NaOH) that exists on the particle surface is easier to separate from the soil particles by the ion exchange of multiply charged positive ions which have a larger gravitational strength. As a result, the sodium alkali spreads widely throughout the soil layer. Calcium hydroxide ($CaOH_2$) adsorbs the surface of clay particles in exchange for other adsorbed ions due to its high gravitational strength, and therefore, calcium alkali is confined to a limited area and spreading is rare. Ordinarily, a ground which requires improvements, such as cement or lime stabilization, consists of soft clay. The surrounding clay soil can be expected to prevent the alkali from migrating and spreading.

5.2.2 Carbonation

Carbonation is also a major function of alkali restraint. Stabilized soil is carbonated and neutralized by being exposed to air. Kitsugi (1989) clarified that free exposure to air leads to the immediate neutralization of alkali in a cement mortal. Even if the exposure to air can not be predicted, the function of the HCO_3^- in the groundwater is expected to function as the neutralization. HCO_3^- in an ordinary river in Japan is measured with 31.0 mg/l. Therefore, a lime-saturated solution, for example, can be neutralized by a dilution of 50 times.

5.2.3 Case Histories and Vegetation

Some data have been obtained through field performances as well as laboratory experiments (Kitsugi 1989). According to the pH value measurements carried out 2-3 months after the column of lime group materials was inserted into the soft clay ground, only the soil 10-30 cm away from the lime column became alkali and the pH of the soils more than 30 cm from the column fell in the range of the one of the original ground.

Cement, lime or other hardening agents can also be used for stabilizing sediment or sludge from the bottom of rivers, harbors, and lakes. Kitsugi (1989) showed that capping the 3-cm thick soil on cement-stabilized sediments was a very effective way to prevent alkali migration leaching from the stabilized soil and the lake water kept neutral. The capping soil can also contain H_2S gas in the bottom layer, but cannot discharge it into the water and consequently, the water quality is kept pure.

An experimental study about vegetation on stabilized soil has also been carried out by Sagara et al. (1994). If stabilized soil is smashed and air-dried, vegetation can grow even after the soil is cured for only a short term, such as 7 days, and its degree is half of the case for untreated soil.

5.2.4 Alkaline Migration Control by Filtration Layer

If soil stabilization by cement, lime or other similar materials is expected to be applied much more widely and if the recycling of excavated surplus soils by soil stabilization is increasingly required, an assessment and the prevention of alkali migration become much more necessary

Table 5.2 Alkali neutralization ability of soils (Miki et al. 1994)

Type of soil	Alkali neutralization ability (mol/g)
Kanto loam	$1.0\text{-}3.0 \times 10^{-3}$
Kanumatsuchi	2.0×10^{-3}
Humic soil	1.0×10^{-3}
Peat	$0.8\text{-}1.0 \times 10^{-3}$
Clayey soil	$6.0\text{-}9.0 \times 10^{-4}$
Pit sand	$1.0\text{-}4.0 \times 10^{-4}$
Silty sand	$2.0\text{-}4.0 \times 10^{-4}$
River sand	$0.5\text{-}4.0 \times 10^{-4}$
Decomposed granite	9.0×10^{-5}
Shirasu	$2.0\text{-}4.0 \times 10^{-5}$

under various conditions of the ground and design methods. An evaluation of the effect of the alkaline restraint of soil is needed in order to assess and control the alkali migration in the ground. Considering the example shown in Fig. 5.1, in which an image of alkali migration for a case using improvement soil for an embankment is given, the buffer ability of the filtration and the cover layer of the untreated soil must be estimated properly as well as the leachate mechanisms of the stabilized soil.

The ability of the alkaline restraint depends on the type of soil. The ability can be expressed as an alkaline neutralization ability, examples of which are shown in Table 5.2 (Miki et al. 1994). The alkaline neutralization ability is considered more practical than the cation exchangeable capacity (CEC), the index ordinarily used, so as to know directly the neutralization ability of the soil.

An evaluation of the combination of a stabilized soil layer and a soil layer for neutralization is also important. Seepage water from the stabilized soil can not be neutralized sufficiently, if the filtration layer is high in permeability and low in alkaline neutralization ability (Mishima et al. 1994, Kamon et al. 1995). It is clarified through an experimental study by Sano et al. (1993) that clayey soil set as a filtration layer around stabilized soil has an effect on the alkaline migration control due to the high neutralization ability of the soil.

A design concept for alkali migration control using a buffer layer is needed to promote the utilization of surplus soil by means of chemical stabilization.

5.3 Alkaline Migration from Stabilized Soil and Buffer Ability of Filtration Soil

5.3.1 Materials Used

Alluvial clay obtained from Osaka Basin and decomposed granite soil from Ohtsu were used in this study. They are typical soils in the western part of Japan. Table 5.3 shows their properties. The alluvial clay was stabilized, while the decomposed granite was used as a filter layer.

Table 5.3 Properties of the used materials

	Alluvial clay	Decomposed granite soil
Particle density (g/cm^3)	2.62	2.64
Natural water content (%)	80.4	7.14
Liquid limit (%)	69.5	-
Plastic limit (%)	31.2	-
Opt. water content (%)	-	18.0
Max. dry density (g/cm^3)	-	1.725
Grain size distribution (%)		
Gravel fraction	0.2	16.2
Sand fraction	2.7	75.4
Silt fraction	59.1	6.8
Clay fraction	38.0	1.6
Permeability (cm/s^2)	-	3.6×10^{-5}
Soil type	CH	S-M
Ignition loss (%)	9.39	-
pH	8.7	5.2
Main mineral	Chrolite, Illite, Smectite	Halloysite, Quartz, Feldspar

Table 5.4 Properties of the stabilized soils

	Stabilized soil I		Stabilized soil II	
Aging (d)	7	28	7	28
Compressive strength (MPa)	0.62	1.01	0.032	0.071
Wet density (g/cm^3)	1.53	1.59	1.27	1.27
Dry density (g/cm^3)	0.90	0.90	0.41	0.42
pH	12.8	12.2	12.9	12.8

It is thought that the buffer ability of a soil depends on the particle size distribution and the composition of clay minerals. The decomposed granite used as the filtration soil is not rich in the clay fraction. Halloysite was detected in an X-ray diffraction analysis as a clay mineral.

Mixing proportions of the stabilized soil were determined according to strength development and permeability. Two types of stabilized soil were used for the following experiments: Stabilized Soil I, an alluvial clay with a natural water content (80.4%) hardened by 10% ordinary Portland cement in dry weight, has high strength and density, while Stabilized Soil II is a liquefied alluvial clay with low strength and density; a 300% water content mixed with 100 kg/m^3 of cement. Table 5.4 shows their properties.

5.3.2 Alkaline Neutralization by Soil

An alkali seepage test was conducted to confirm the importance of the alkaline neutralization ability. A column of decomposed granite 15 cm thick was set by compaction, in a cylindrical

PVC mold 20 cm in height and 5.1 cm in diameter, in an optimum water content (18%), and a saturated solution of $Ca(OH)_2$ was seeped from the top of the soil. pH values were measured after the seepage of the required amount. Figure 5.2 shows the experimental results. The high alkali territory is limited, but spreads as the alkaline solution seeps. Neutralization does not occur uniformly in the soil layer. Only the soils that balance with the quantity of alkali exhibit high pH values. This means that if the alkaline leachate exceeds the neutralization ability of the filtration soil layer in the field, high alkaline water will suddenly be discharged outside.

Alkaline neutralization by the decomposed granite soil was measured. The soil was mixed in various mixing proportions with $Ca(OH)_2$ solutions at various concentration levels, and the pH of the suspension was measured 2 hours later. The added OH^- can be calculated based on

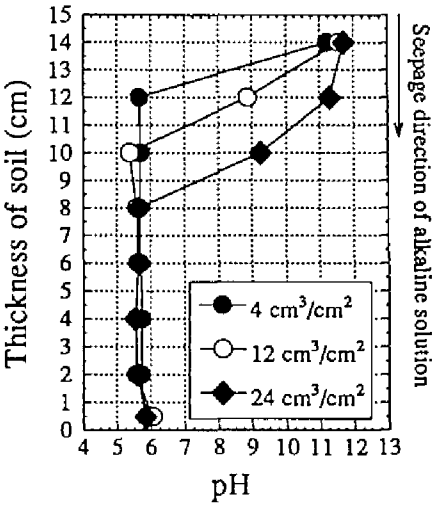


Fig. 5.2 pH in the compacted decomposed granite after the alkaline seepage

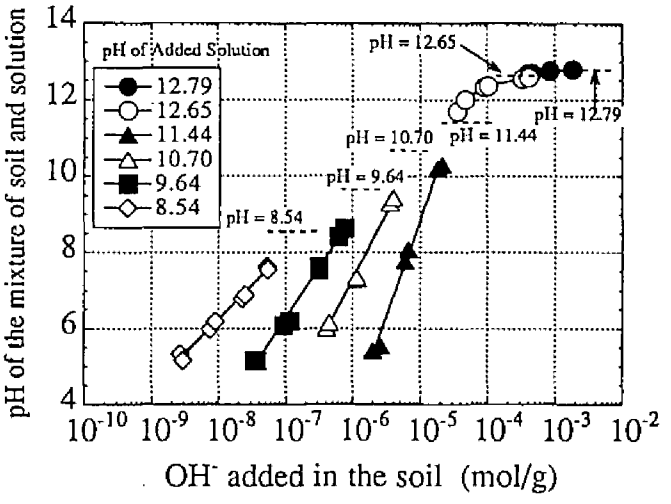


Fig. 5.3 Alkaline buffer ability of decomposed granite

the concentration as well as the proportion of the soil and the solution. Figure 5.3 shows the relationship between the added hydroxide ion (OH^-) per granite soil in dry weight and the pH value of the suspension. The curve depends on the initial pH value. That is, the larger quantity and the lower concentration of the initial solution causes a consequent high pH of the suspension. The behavior is not incompatible with the adsorption theory. If the initial pH exceeds 12, the pH of the suspension decreases to slightly lower than the initial pH. An initial pH lower than 12 leads to a remarkable decrease in the pH of the suspension. About 10^{-4} mol/g of added OH^- may be the dividing line between the behaviors, that will allow for the alkaline neutralization ability.

Relationships between the added OH^- and the neutralized OH^- per 1 g of soil are expressed in a curve in Fig. 5.4. Most of the added OH^- can be neutralized if the initial OH^- level is lower than 10^{-5} mol/g. However the neutralization is not effective when an OH^- higher than 10^{-4} mol/g is added, which indicates that neutralization by soil has its limit.

The neutralized OH^- can be calculated as the following equation:

$$C' = (10^{(pH-14)} - 10^{(pH'-14)}) \times V / W \qquad \text{(Eq. 5.2)}$$

where

C' : OH^- neutralized (mol/g),

pH : initial pH of added solution,

pH' : pH of suspension,

V : volume of added solution (l),

W : mass of soil (g) .

The alkali neutralization ability, C (mol/g), is defined as the maximum quantity of OH^- that

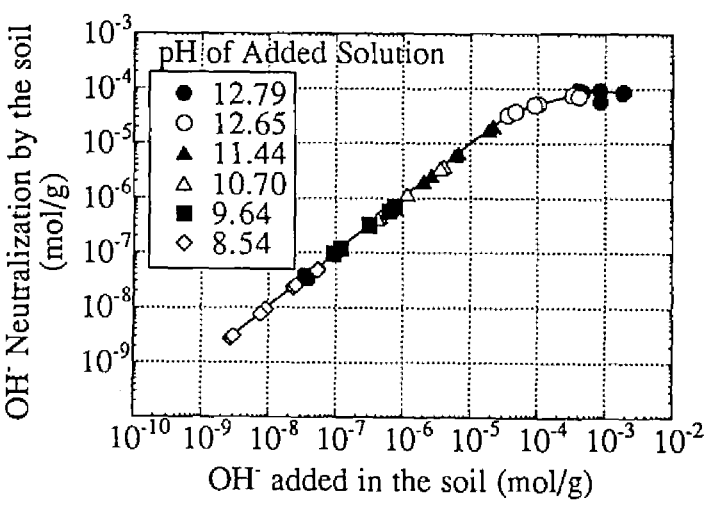


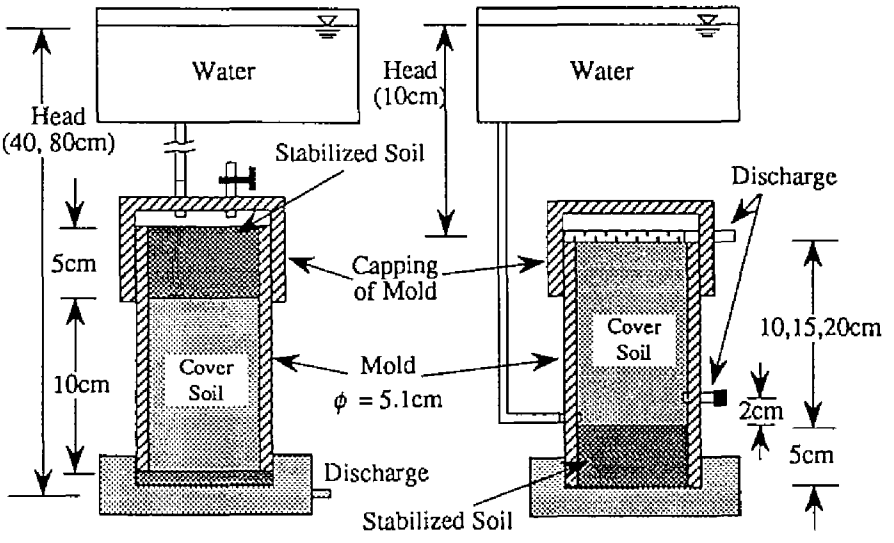
Fig. 5.4 Alkaline neutralization ability of decomposed granite soil

can be neutralized by 1 g of soil. The alkali neutralization ability of the soil can be determined as 9×10^{-5} mol/g from the curve in Fig. 5.4. Miki et al. (1994) also measured the alkaline neutralization ability of 10 typical soils using the saturated solution of $Ca(OH)_2$, as shown in Table 5.2. The neutralization ability of decomposed granite is similar in value to the ability presented here, but is comparatively lower than that of the clayey soils.

5.3.3 Alkaline Migration through Stabilized Soil

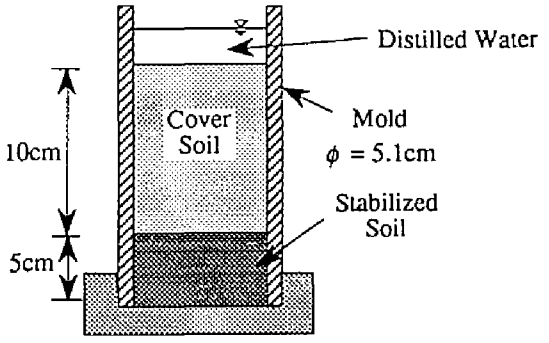
(1) Seepage through Stabilized Soil

To express a case in which water can permeate through stabilized soil as well as through the filter layer, seepage tests were carried out on the specimens as shown in Fig. 5.5 (a). A cylindrical mold was filled with Stabilized Soil II (liquefied stabilized soil) and the decomposed granite was compacted at the optimum water content. After aging for 7 days, the composite soil specimens were subjected to water head. The amount and pH value of the discharged water were measured continuously during seepage, and the pH distributions in stabilized or untreated



(a) Alkaline Transport in Cover Soil through the Stabilized Soil

(c) Alkaline Transport in Cover Soil on the Stabilized Soil



(b) Alkaline Diffusion in Cover Soil from the Stabilized Soil

Fig. 5.5 Experimental equipment on alkaline migration

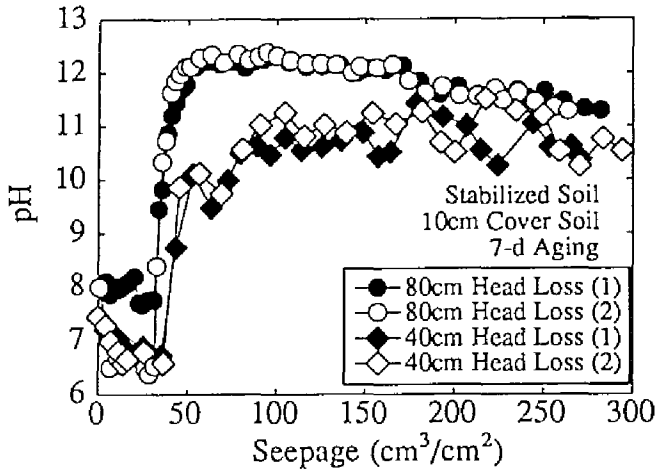


Fig. 5.6 pH of discharge from the stabilized soil

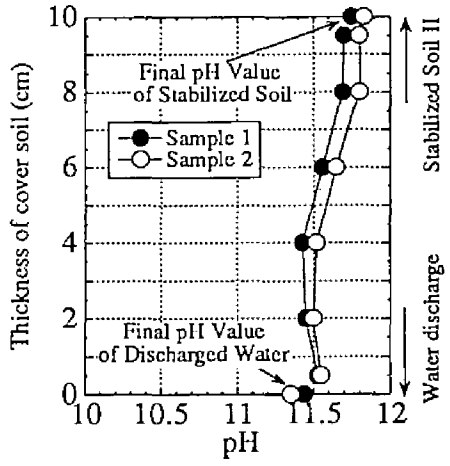


Fig. 5.7 pH distribution in cover soil after alkaline seepage

layers were also measured after seepage.

As shown in Fig. 5.6, which indicates pH changes in the discharge, water at a pH higher than 11 was discharged continuously after the seepage exceeded about 32-37 cm^3/cm^2. As shown in Fig. 5.7, the pH in the filtration layer after seepage was in the range of high alkali, which indicates that the neutralization ability of decomposed granite soil was almost completely exhausted. The discharged pH is affected by the water head, as shown in Fig. 5.6, because it depends on the flow rate. In the case of a lower water head (40 cm), a low pH solution was discharged for a longer period. Even after the discharged pH became alkali, the pH was below 11, lower than in the case of a higher water head.

Based on the results stated in Section 5.2 that the neutralization ability of decomposed granite is 9×10^{-5} mol/g and the assumption that the pH of water immediately after permeating through the stabilized soil is 12.6, the seepage volume required for a pH higher than 8.6 can be calculated to be approximately 60 cm^3/cm^2. This is 1.5-2.0 times higher than the experimental

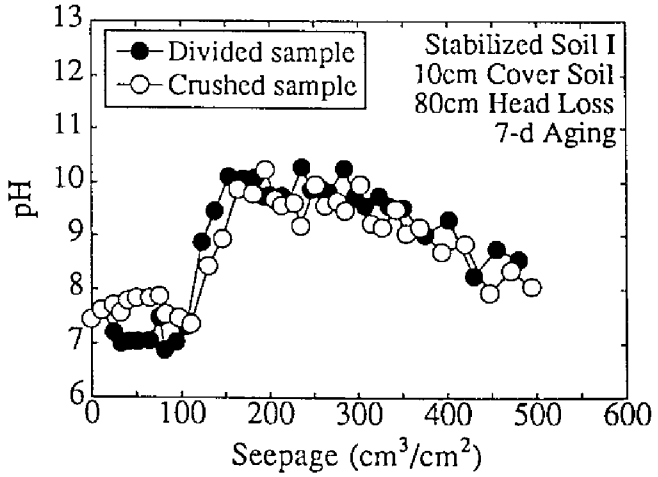


Fig. 5.8 pH of discharge from the crushed stabilized soil

results of 32-37 cm^3/cm^2. The reasons for this difference might be that alkaline seepage penetrates along a certain path in the filter layer and consequently only comes in contact with selected particle surfaces for the neutralization, and that alkali neutralization depends on the added OH^-, rather than the concentration in the soil-water systems, as discussed in Fig. 5.4. The flow rate may also affect the neutralization phenomenon.

(2) Seepage through the Crushed Stabilized Soil

Similar experiments could not be conducted on Stabilized Soil I because of its low permeability. However, seepage can permeate through a layer of crushed specimens of Stabilized Soil I. In these experiments, the stabilized soil was cut into 4 sections or crushed into pieces 2-5 mm in diameter. As shown in Fig. 5.8, the discharged water became alkaline after a seepage of 2200 ml, but it exhibited a lower pH than in the case of Stabilized Soil II, and the pH did not keep its high value but decreased. One reason is that the seepage water only comes in contact with the surface of the divided blocks of the stabilized soil, and does not seep into the blocks. And, the discharge of alkali from the stabilized soil was limited in comparison to the permeable stabilized soil. Therefore, the permeability of stabilized soil is an important factor for assessing alkaline migration.

5.3.4 Alkaline Diffusion from Stabilized Soil

(1) Alkaline Diffusion and Buffer in Soil

The alkaline diffusion mechanism is important as well as the neutralization ability of the soil. The experiment shown in Fig. 5.5 (b) was carried out to assess the alkaline diffusion from the stabilized soil. The bottom of the mold was filled with Stabilized Soil I, 5 cm thick, and decomposed granite was filled in above it by compaction with the optimum water content. Distilled water was added after 7 days of curing and left there for 94 days.

As shown in Fig. 5.9, only the soil located 0-3 cm above the stabilized soil exhibited a higher pH than 10, while the pH of the soil located more than 3 cm away from the stabilized

layer just about kept the original pH of the decomposed granite soil. This shows that calcium alkali cannot diffuse for a long distance and the pH distribution remains balanced. According to the diffusion coefficient of ions, summarized by Shackelford and Daniel (1991), the diffusion coefficient of the hydroxide ion is higher (52.8 m^2/s) than that of other ions, but the calcium ion, which is electrically counterbalanced with a hydroxide ion here, has a low diffusion coefficient (7.92 m^2/s).

(2) pH of Water Flow on the Surface of the Stabilized Soil

As discussed in Section 5.3.3, the permeability of the stabilized soil influences the discharge of the alkali solution. The pH changes in the filtration layer above the stabilized soil with low permeability were tested with the seepage cell shown in Fig. 5.5 (c). The decomposed granite was filled 10, 15, and 20 cm thick by compaction on top of 5 cm of Stabilized Soil I in the

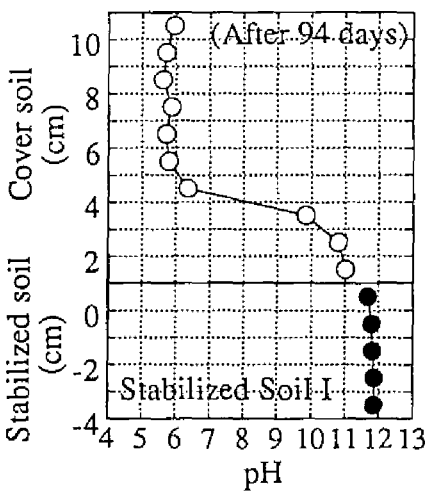


Fig. 5.9 pH distribution in the stabilized soil and the cover soil

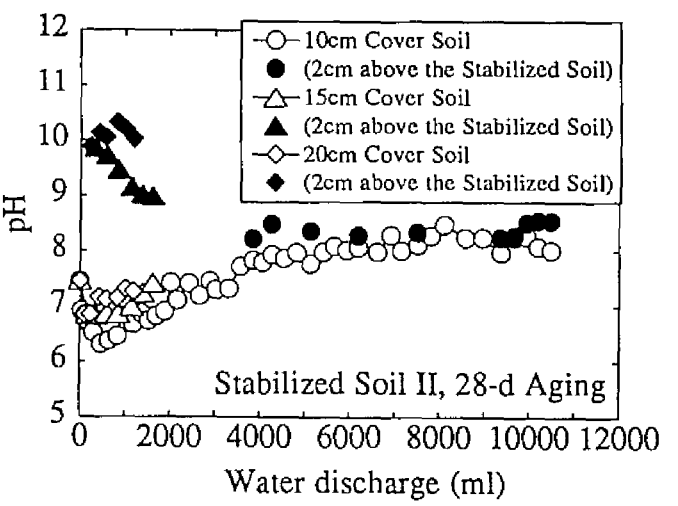


Fig. 5.10 pH value of discharge from the cover soil

cylindrical mold. After curing for 28 days, the seepage was poured into a filter layer at a point close to Stabilized Soil I and discharged from the top of the layer due to the water head, as shown in Fig. 5.5 (c). Therefore, the seepage did not pass through the stabilized soil, but only came in contact with the surface of the stabilized soil. During seepage, the pH of the discharged water was measured constantly while the water was sampled from a point 2 cm above the stabilized soil for pH measurements at intervals.

From the results shown in Fig. 5.10, the pH value of the discharge from the top increased as the seepage proceeded, but remained neutral and could not become alkaline. The pH close to the stabilized soil (2 cm above) was high at an early stage (about 10) and decreased as the seepage proceeded. At the stage later than 4000 ml of seepage, the discharge close to the stabilized soil exhibited a pH similar in value to that discharged from the top of the filter. This tendency indicates that the alkali was distributed, and consequently, diluted uniformly in the filter layer as the alkali could only be supplied from the surface of the stabilized soil layer.

(3) Tank Test for Alkaline Migration

The tank test was performed to evaluate alkali migration in a two-dimensional flow. A description of the test can be found in Fig. 5.11. The tank was 20 cm in width, 55 cm in height, 250 cm in length, and at an incline of 2 %. Stabilized Soil I was filled in at the bottom, 5 cm thick, except for 30 cm towards the lower end of the tank. Stabilized Soil I was overlain by a compacted filter layer (30 cm at Stabilized Soil I and 35 cm at the lower end of the tank). After 7 days of curing, the tank was filled with tap water. Water was drained at the bottom of the lower side of the tank, point A in Fig. 5.11, for 66 days. The water was also sampled above the stabilized soil at points B, C, and D in Fig. 5.11, using a pipe which connected the points from the outside, at 7-day interval for pH measurements. After 66 days, the total water discharge was 14,000 ml, which is the estimated amount of seepage for half a month of annual rainfall. One third of the total annual rainfall (1760 mm) is considered to be retained in the soil. After the test, the pH distribution in the soil was measured.

Figure 5.12 exhibits the pH tendency of the discharged water. The pH values were varied,

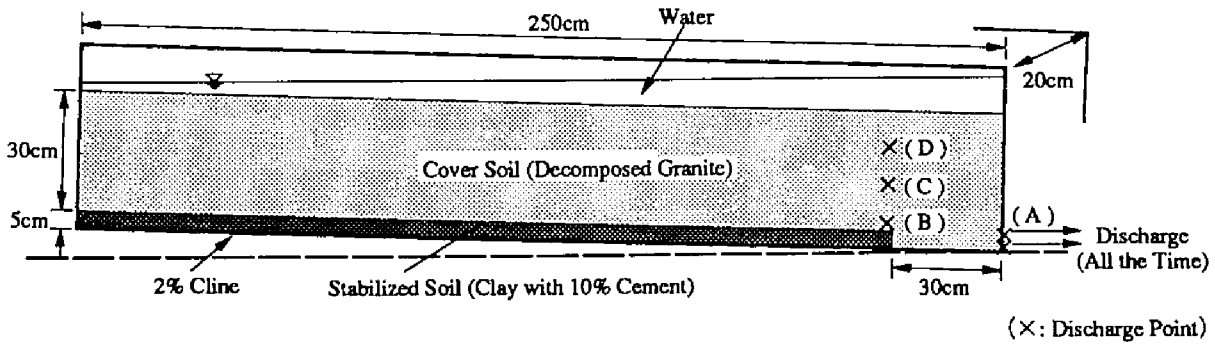


Fig. 5.11 Equipment for tank test

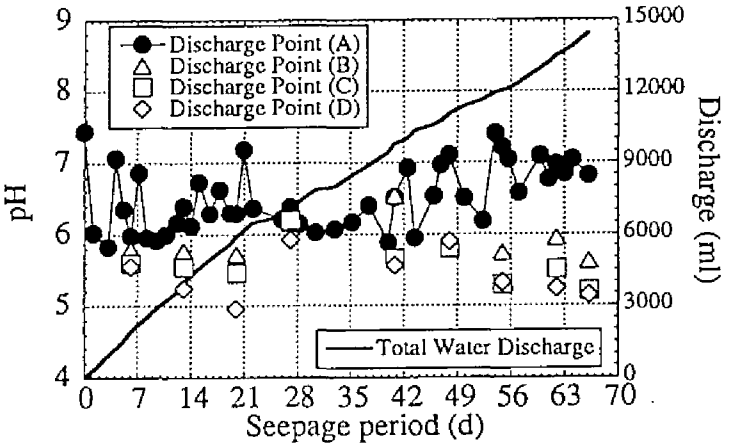


Fig. 5.12 pH characteristics versus seepage period in tank test

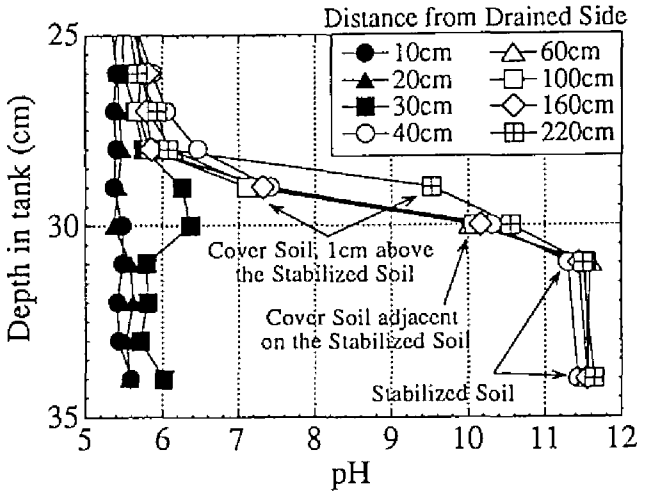


Fig. 5.13 pH distribution of soils after the tank test

but were within the range of neutral and weak acid, while alkaline leachate did not exist. The reason for the weak acid in the discharge is that the decomposed granite soil is itself a weak acid.

Figure 5.13 shows the pH distribution in the soil after seepage. While the stabilized soil had a pH higher than 11, only the decomposed granite soil 0-1 cm above the stabilized soil was alkali (pH 10-11 and 7-10 respectively), and the soil more than 2 cm above the stabilized soil maintained the weak acid of decomposed granite soil. From the results of the cover soil, 1 cm above the stabilized soil, the pH decreased as the measurement point approached the drained side. This is because the dilution occurred due to the chemical diffusion and water flow.

In conclusion, the low permeability of stabilized soil and the surrounding cover layer is necessary for the control of alkali migration, and the alkaline solution is contained within the cover soil close to the stabilized soil in spite of its low alkaline neutralization ability.

5.4 Alkaline Migration Control due to Cement-Stabilized Soil

5.4.1 Description of Parametric Analysis

An analytical study was performed to discuss the design concept for alkaline migration control based on the test results presented above. In order to apply the stabilized soil to embankments, the filter layer thickness required for alkaline leachate control was calculated through a parametric analysis.

The typical cross section of the embankment shown in Fig. 5.1 was simplified to that shown in Fig. 5.14. As shown in Fig. 5.1, two types of water flow can be considered in the stabilized embankment. The one is the water flow which only passes in the cover layer and does not seep into the stabilized soil. The other type is the flow which passes through the stabilized soil and reachs the lower layer. In order to assess the effect of drainage ability of cover soil as well as the effect of neutralization ability of filtration layer, seepage quantity into the stabilized soil is calculated in relation to the permeability and the width of cover soil and stabilized soil, as shown in Fig. 5.14. As the actual embankment has a inclined slope, the seepage water in the inclined cover layer seeps into the stabilized soil gradually as it flows down. In this simplified model shown in Fig. 5.14, the side of embankment is vertical, and it is assumed that the water is distributed into the stabilized soil and the cover soil from the beginning of the seepage.

A high alkaline solution will be generated if the seepage passes through the stabilized soil, and it will be neutralized during passage through the filter layer below the stabilized soil. We calculated the thickness of the filter layer that can neutralize the alkaline solution discharged from

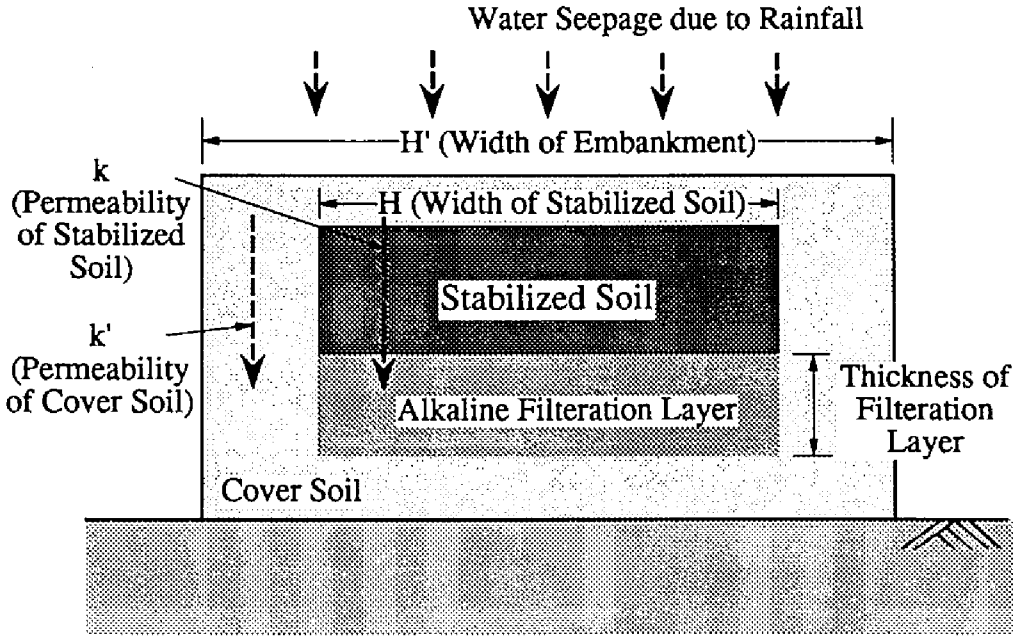


Fig. 5.14 Simplified cross section for parametric analysis of alkaline migration

the stabilized soil. The criterion is a pH level lower than 8.6, which is the effluent standard in Japan. The assumptions for the analysis are as follows:

(1) The seepage water flows only vertically.
(2) The hydraulic gradient of the embankment is constantly 1; there is no influence on the calculated results when the permeability is higher than 10^{-8} cm/s.
(3) The alkaline diffusion in the cover soil is not taken into account to be based on the experimental results.
(4) Only the soil below the stabilized soil can neutralize the alkaline, which is indicated as an alkaline filtration layer in Fig. 5.14.
(5) The amount of seepage into the ground is 1/3 the average annual rainfall in Japan (1760 mm).
(6) Discharged water from the stabilized soil constantly has a high pH; the pH was given parametrically.
(7) A simplified model section is two dimensional; the axis direction of the embankment is not considered.

Seepage quantity, L *(mm)*, is according to;

$$L = 1760/3 \times T/(1+k'/k(H'/H - 1)) \qquad \text{(Eq. 5.3)}$$

where k, k', H, and H' are mentioned in Fig. 5.14 and T is the supposed period (y). H/H' and k/k' are defined as the width ratio and the permeability ratio, respectively.

If the discharge from the stabilized soil is neutralized by alkaline neutralization ability of filter layer, Eq. 5.3 should be satisfied.

$$C > (10^{(S-14)} - 10^{(8.6-14)}) \times V/W \qquad \text{(Eq. 5.4)}$$

where C (mol/g) is the alkaline neutralization ability of the filtration soil, S and V (l) are the pH value and the quantity of the discharge for the seepage through the stabilized soil, respectively, and W (g) is the total mass of the filtration soil under a dry condition. As W and V can be expressed by H and L, the thickness of the filtration layer by x (cm), and the dry density of the filtration soil by ρ_d (g/cm^3), Eq. 5.4 can be reduced to

$$x \geqq (10^{(S-14)} - 10^{(8.6-14)}) \times 10^4 L / (\rho_d C). \qquad \text{(Eq. 5.5)}$$

According to the Eqs. 5.3 and 5.5, the thickness of the filtration layer required for alkaline neutralization was calculated by the following equation:

$$x \geqq 17600000/3 \times (10^{F-14} - 10^{8.6-14})/(1+k'/k(H'/H-1)) \times T/(C \cdot \rho_d). \qquad \text{(Eq. 5.6)}$$

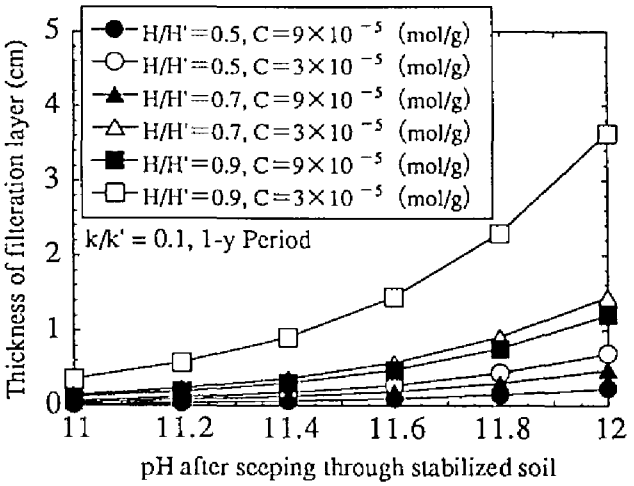


Fig. 5.15 Required thickness of filteration layer in stabilized soil embankment

In this study, S, k/k', and H/H' were given parametrically, ρ_d is 1.73 g/cm^3, and C is 9×10^{-5} mol/g, based on the experimental results, or is 3×10^{-5} mol/g, considering the difference between the experiment and the calculation.

5.4.2 Results and Discussions of the Parametric Analysis

Figure 5.15 shows the filter layer thickness required for the alkaline neutralization for 1 year of rainfall. The required thickness depends not only on C, but also on H/H' and S. Even under the severest conditions when S = 12, H/H' = 0.9, and $C = 3\times 10^{-5}$ mol/g, the required thickness is estimated at 3.6 cm. As the analytical results are strongly affected by S, the decision of the initial pH, S, is important for calculating the required thickness. The pH of stabilized soil, S, was constant in the present analysis, but it might decrease due to carbonation in the field, as stated in Section 5.2 (Kitsugi 1989). After obtaining a more precise relationship between the pH change versus time ratio, we can realize a better estimation. Considering the influences of the width ratio, H/H', one effective option for alkaline migration control is for more seepage water to pass through only the cover soil and less through the stabilized soil due to the dimensions of the embankment.

Figure 5.16 shows the required thickness for 30 years of rainfall when H/H' is 0.9, which is most probable under actual conditions. The required thickness of the filtration layer is influenced not only by the neutralization ability of the soil, but also by the permeability ratio. When the stabilized soil has as high a permeability as the filtration soil (k/k' = 1.0), the filtration layer must be at least 200 cm thick for alkaline migration control under the severest conditions (S = 12.0 and $C = 3\times 10^{-5}$ mol/g). As the permeability ratio decreased, the required thickness decreased markedly. Thus, the permeability of soils is very important. Due to the influence of the permeability ratio, one of the most effective options was confirmed to be less seepage water

passing through the stabilized soil. This means that the stabilized layer should be carefully constructed as a low-permeable layer, when environmental influences must be considered.

The calculated results shown in Figs. 5.15 and 5.16 are based on the supposed case in which decomposed granite or another similar sandy soil is used as the filtration layer. Figure 5.17 summarizes the required thickness of the filtration layer with respect to the more varying values of the neutralization ability, considering many kinds of soil for the filtration layer. The range of the neutralization ability of 5 types of soil obtained by Miki et al. (1994) are also presented in Fig. 5.17. From these results, soil which has a high alkaline neutralization ability should be used as the filter soil to effectively control alkali migration. In particular, the minimum thickness of the filtration layer was calculated at less than 10 cm in the case of using

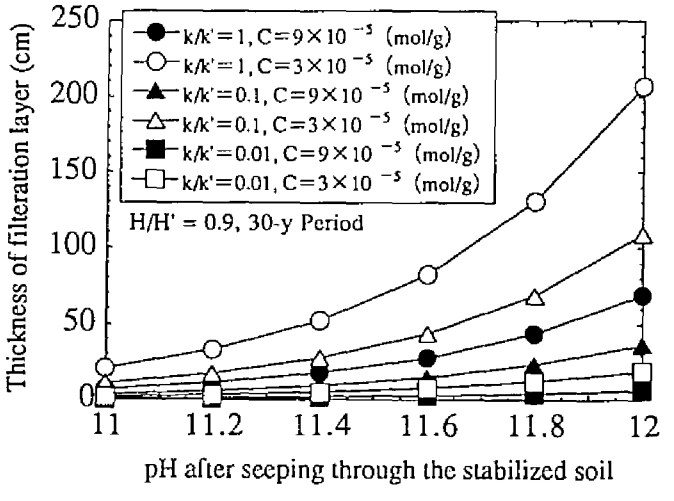


Fig. 5.16 Required thickness of filteration layer in stabilized soil embankment

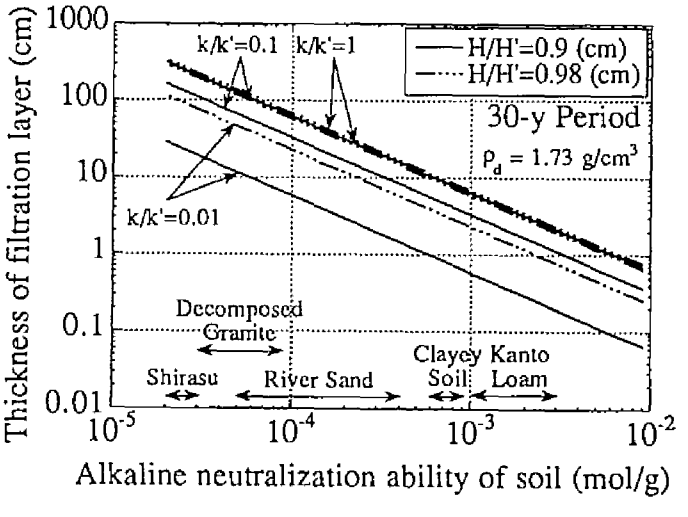


Fig. 5.17 Required thickness of filtration layer in stabilized soil embankment

clayey soil and Kanto Loam. However, we must take into account other factors besides the alkaline neutralization ability. When we suppose a natural ground of Kanto Loam as the filtration layer, there are many cases in which the ground has some cracks or pipe-shaped voids. And, as the seepage water is consequently passing through only selected voids, it might be impossible to expect the neutralization ability of all particles. In addition, soil that has a high neutralization ability usually consists of fine grain particles and is difficult to use as a filtration layer by compaction in the field. The soil should be used as a stabilized soil rather than as a filtration soil. Even if such a soil can be constructed as a filtration layer, the layer will be low in permeability and the required thickness of the layer will increase, as previously stated. Therefore, the permeability and the workability of the soil as well as the alkaline neutralization ability should be noticed. In the case of using decomposed granite soil, which is widely distributed in the western part of Japan, it will be reasonably applicable to the filtration layer in terms of workability and permeability, because the required thickness was calculated at approximately 30 cm when the filter soil was high enough in permeability in comparison to the stabilized soil. It should be emphasized that the stabilized layer must be constructed carefully to become a low-permeable layer in order to control the environmental impact caused by the alkali migration from the stabilized materials.

5.5 Conclusions

In this chapter, the alkaline migration mechanisms from stabilized soil and the concept of their control were discussed through experimental and analytical studies. The content presented here described one of the major problems with the environmental influences caused by the geotechnical utilization of by-products. Many types of by-products are required for use as construction materials in large quantities, and one effective option for this might be the use of cement or lime stabilization. Surplus soil as well as industrial waste are generated in large quantities, which cause social and environmental problems. Cement or lime stabilization is the traditional method and it should continue to be utilized in order to prepare these by-products for recycling. However, for utilization purposes the environmental influences of alkaline leachate from materials stabilized by cement must be addressed and a control method is needed. In this chapter, we discussed the effect of a filtration layer around stabilized soil for alkaline migration control. The main results obtained here can be summarized as follows:

(1) The alkaline neutralization ability of a soil for a filtration layer has its limits. When the seepage quantity exceeds the criteria, the alkaline solution may leach from the filter soil. The criteria can be roughly estimated from the alkaline neutralization ability of the soil, and therefore, a measurement of the alkaline neutralization ability is important for assessing the alkaline leachate from earthen structures.

(2) If the stabilized soil has low permeability, seepage water can not penetrate and pass through the stabilized interior, and thus, there is little possibility of alkali leachate. If the permeability is high due to low density or the incidence of cracks, seepage water can flow through the stabilized layer and alkali leachate can occur.

(3) If the seepage water flows only into the cover filtration layer but does not pass through the stabilized soil, the alkaline will be little diffused, and consequently, it will be diluted despite its alkaline neutralization ability. Only the filtration layer very close to the stabilized layer will be alkali.

(4) A design concept for alkaline migration control was discussed for its application to embankments. We must consider not only the neutralization ability of the filtration soil, but also the permeability of materials and the geometric dimensions of earthen structures. One of the most effective options is to prevent seepage water from passing through the stabilized layer.

References for Chapter 5

Amano, H., & N. Masumoto (1980). "Alkaline leachate from cement stabilized soil," *Proc. 34th General Meeting of CAJ*, pp.472-475 (in Japanese).

Bialucha, R., J. Geiseler and K. Krass (1994). "Assessment of the environmental compatibility of industrial by-products and recycled materials," *Environmental Aspects of Construction with Waste Materials*, J.J.J.M. Goumans et al. (eds.), Elsevier Science, pp.719-726.

Fällman, A.M., and J. Hartlen (1994). "Leaching of slags and ashes," *Environmental Aspects of Construction with Waste Materials*, J.J.J.M. Goumans et al. (eds.), Elsevier Science, pp.39-54.

Kamon, M., T. Katsumi and S. Oyama (1995). "Environmental impact and control of alkaline migration by cement stabilized soil," *Annuals, Disas. Prev. Res. Inst., Kyoto Univ.*, No.38 B-2, pp.55-65, 1995 (in Japanese).

Kitsugi, K. (1989). "Environmental aspects accompanied with weak soil ground improvement techniques - Countermeasures against pH problems on soil improvement methods," *Cement & Concrete*, No.511, pp.104-115 (in Japanese).

Miki, H., N. Mori, and T. Hurusho (1994). "Experimental study on alkaline neutralization ability and alkaline seepage of the soil," *Proc. 49th Annual Meeting of JSCE*, Vol.3, pp.1534-1535 (in Japanese).

Ministry of Construction (1994). *Technical Manual for Recycling of Surplus Soil* (in Japanese).

Ministry of Construction (1995). *Investigation on generation and management of by-product from construction works* (in Japanese).

Mishima, N., K. Hoshino, H. Ishihara and K. Terao (1994). "Adherence to pH of soils," *Proc.*

29th Annual Meeting of JSSMFE, pp.2327-2328, (in Japanese).

Mitchell, J.K. 1992. *Fundamentals of soil behavior, second edition*, John Wiley & Sons, Inc.

Sagara, M., H. Sakamoto and M. Nakamura (1994). "Influences of the cement stabilized soil on the vegetation," *Proc. 49th Annual Meeting of JSCE*, Vol.3, pp.1592-93, 1994 (in Japanese).

Sano, M., M. Yamamura, K. Kitugi and T. Sinkosi (1993). "Experiment results on the prevention effect within cohesive soil ground on immigration of lime-alkalinity adjacent to lime-treated soil mass," *Proc. Annual Meeting of JSSMFE*, pp.2585-2588 (in Japanese).

Shackelford, C.D., and D.E. Daniel (1991). "Diffusion in saturated soils," *Jour. Geotech. Engrg., ASCE*, Vol.117, No.3, pp.467-484.

Yong, R.N., A.M.O. Mohamed & B.P. Warkentin 1992. *Principles of contaminant transport in soils*, Elsevier.

CHAPTER 6

Conclusions

The author discusses the utilization of waste materials through a geotechnical stabilization method from the standpoint of environmental geotechnology. To promote geotechnical waste utilization, the possibility for creating a more positive environment through geotechnical waste utilization is proposed. A negative environmental impact by the reuse of waste materials and methods to control it is also presented. The main results are summarized as follows:

In Chapter 1, the objectives and the contents of the thesis were presented and general information on the background of related fields was addressed.

In Chapter 2, the author discussed the effectiveness of the stabilization and utilization of ash and slag materials, namely, fluidized bed combustion coal fly ash (FCA), stainless-steel slag (S-slag), and municipal solid waste incinerated fly ash (MSW fly ash). Due to its lime and gypsum contents, FCA showed remarkable strength development by compaction with or without a hardening agent, and thus, may be utilized as an embankment or road subbase material. The "Non-Dusty Method," which adds waste oil, prevents dust effectively. The characteristics of the material thus treated, with respect to hardening under soaking conditions, are applicable to utilization for earthen works. The addition of FCA contributes to the stabilization and/or solidification of a soft ground with or without Carbonated-Aluminate Salt (CAS). The field-scale tests showed that general construction concepts and equipment are available for the proposed method.

S-slag, typical electric reducing slag, was evaluated to establish its potential reuse as a geo-material in view of physical properties and chemical composition. The use of CAS accelerates the formation of the hydrated by-products of CSH ($CaO \cdot SiO_2 \cdot H_2O$) and CASH ($CaO \cdot Al_2O_3 \cdot SiO_2 \cdot H_2O$). These hydrates contribute to the strength development of S-slag mixtures. With the addition of kaolinite, the specimens showed an improvement in durability. And as a supplement of fine grain materials to S-slag brought about denser mixtures. The durability of hardened S-slag mixtures depends on their material properties as well as the curing conditions. A drying

condition with a raised temperature can promote the hardening reaction of stabilized S-slag mixtures. The Vacuum drying method, proposed in this study, is effective for assessing the drying-wetting durability of chemically stabilized mixtures because it enables sufficient dehydration of the specimens while sufficiently maintaining a constant and normal temperature. In conclusion, S-slag has the potential for use as a subbase course material if it is treated with CAS and kaolinite.

In terms of the stabilization of municipal solid waste incinerated fly ash (MSW fly ash), the multiple use of cement and FCA as an MSW fly ash stabilizer can bring about strength development, high soaking durability, and the containment of heavy metals. The method is effective for environmental landfilling of MSW fly ash. The behavior of soluble salts contained in the MSW fly ash can greatly influence the strength development, the soaking durability, and the hardening reaction of the stabilized mixtures.

In Chapter 3, the treatment of sludge discharged from construction works was discussed for utilization purposes. Through an evaluation of the hardening effect of cement or cement group materials, sludge with a high water content could be stabilized by hardening agents (with about a 200 kg/m^3 additive content) so that the stabilized sludge could be utilized as an earthen material, such as subgrade or an embankment. The hardening mechanisms of sludge stabilization are clarified. Calcium aluminate carbonated hydrate ($7CaO \cdot 2Al_2O_3 \cdot CaCO_3 \cdot 32H_2O$) as well as ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 24H_2O$) were detected and are considered to promote strength development. The strength development characteristics are reflected by the type of stabilizer. With regard to the drying-wetting conditions, the strain accumulation caused by dry shrinkage and the disappearance of reactive products have an influence on the durability. These influences are strongly affected by the developed strength as well as by the soil properties, water content, and type of hardening agent.

A system which utilizes waste slurry and consists of dehydration or solidification was proposed. It was found that the density (ρ) and the funnel viscosity (μ) of waste slurries can be used effectively as indexes with which to judge whether a slurry would best be treated by dehydration or by solidification for recycling purposes. Carbonated-Aluminate Salt (CAS) as a flocculant in the utilization system can form large and durable flocs rapidly. The flocs can easily be dehydrated and the water which is discharged is clear enough to satisfy environmental quality standards. The solidification method by means of FCA and CAS is very effective for treating high density or high viscosity waste slurry. A well-mixed waste slurry with stabilizers is highly homogeneous, reasonably strong, and durable against soaking or remolding. Therefore, it can be used effectively as embankment or subgrade material. The utilization system is practicable from the viewpoint of the complete utilization of waste slurry as a construction material.

In Chapter 4, a new technical method, the "Bagged WRP Method," for utilizing waste rock

powder (WRP) was proposed from the standpoint of waste utilization and environmental mitigation. WRP-CAS mixtures have a highly solidified strength, low density, and high permeability due to the reactive characteristics of CAS and the basic properties of WRP. As for the basic properties of the bagged WRP-CAS mixtures, the hardening reaction proceeds immediately after soaking and high strengths are obtained. The mixtures are both light in weight and high in strength when cured in sea water or other experimental conditions which provide a compressive strength of 50-600 kPa and a wet density of 1.6-1.8 g/cm^3. The method can be conducted with traditional equipment. No remarkable changes in the quality of the sea water, in terms of environment impact (e.g., in pH), were observed during the execution or curing of the bagged WRP. A stability analysis clarified that bagged WRP is more advantageous to sunken-levee construction than rock or concrete blocks because it is light in weight and ground improvement work is not necessary. In conclusion, the Bagged WRP Method not only has an effect on the sunken-levee application, but also extends to the applicability of the levee construction itself. To minimize environmental damage and achieve the concept of sustainable development, the construction of man-made tidal flats is required as a substitute for those which will be destroyed by construction works. Sunken-levee construction is needed in order to retain the soil materials in the tidal flats. The Bagged WRP Method represents a useful new strategy for waste management as well as for environmental mitigation.

From Chapter 2 to Chapter 4, the chemical mechanisms of stabilization of waste materials were discussed. Certain kinds of hydrated by-products, namely, ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$), CSH ($CaO \cdot SiO_2 \cdot H_2O$), CASH ($CaO \cdot Al_2O_3 \cdot SiO_2 \cdot H_2O$), and calcium aluminate carbonated hydrate ($7CaO \cdot 2Al_2O_3 \cdot CaCO_3 \cdot 24H_2O$) were detected through X-ray diffraction (XRD) analysis and scanning electronic microscope (SEM) observation. These compounds have been ordinarily detected in the soil stabilized by cement or lime. Ettringite and calcium aluminate carbonated hydrate contributed effectively to the strength development of stabilization of the waste sludge with remarkable high water content due to their chemical composition. Ettringite also had an effect on the applicability of the Bagged WRP Method because of its expansive and immediate hardening characteristics. The formation of CSH and CASH secured the high strength and durability of stabilized FCA and S-slag, while ettringite was sensitive to drying-wetting conditions. Further research is required in order to evaluate the compatibility of waste materials and stabilizers in detail, and to predict the stabilization effect.

Chapter 5 dealt with the environmental impact caused by the geotechnical recycling of surplus soils stabilized by cement. The alkaline neutralization ability of a soil for a filtration layer has its limits. When the seepage quantity exceeds the criteria, the alkaline solution may leach from the filter soil. The measurement of the alkaline neutralization ability is important to assessing the alkaline leachate from earthen structures in order to estimate this criteria. If the seepage water flows only in the cover filtration layer but does not pass through the stabilized

soil, due to its low permeability, there is little possibility of alkali leachate because the alkaline will be slightly diffused, and consequently, it will be diluted despite its alkaline neutralization ability. If the permeability of a stabilized soil is high, due to low density or the incidence of cracks, seepage water can flow through the stabilized layer and alkali leachate can occur. A design concept for alkaline migration control was proposed for its application to embankments. We must consider not only the neutralization ability of the filtration soil, but also the permeability of the materials and the geometric dimensions of the earthen structures. One of the most effective options is not to allow seepage water to pass through the stabilized layer.

Issues on waste management are strongly affected by the future prospects of our society and its social conditions. In the construction industry, waste management is related to future trends, such as major projects accompanied by large-scale developments and the use of underground or offshore spaces, and environmental preservation due to construction works. Reducing the generation of waste and promoting the reuse and recycling of waste will therefore be continuously encouraged. The following issues should be addressed in relation to future trends in geotechnical waste utilization.

(1) To establish the concept of quality control assurance of waste stabilization and utilization.

The waste material is a by-product, but not a product. Therefore, the physical and chemical properties of the waste materials are widely varied due to the variety of raw material, the variety of treatment process, and other unexpected factors. In this study, the samples which were experimentally used for the assessment for stabilization and utilization were the representatives of the materials. In futhre, we must consider the variety of the properties of waste materials which will be applied to geo-materials, and must establish the concept of quality control assurance of stabilization and utilization of waste materials.

(2) To establish soft technology and concepts for promoting geotechnical waste utilization.

Many problems with soft technology and its concepts need to be solved in order to promote waste recycling, while discussions have mainly been restricted to aspects of hard technology. The re-arrangement of legislation, the re-estimation of authorized standards, the application of risk assessment concepts, and environmental ethics can be listed as soft technology and its concepts.

Present legislation in Japan restricts the utilization of waste. Once a material is regarded as waste, it must continue to still be referred to as waste even if it has been highly improved for recycling. Materials should be deemed as waste (or not), on the basis of their composition and properties and not on their origin. The construction industry should be required to contribute to the establishment of material standards for waste recycling from the standpoint of being potential users of waste materials.

To re-estimate authorized standards and design methods will have a strong effect on elevating waste utilization. At present, authorized standards and methods are only for the use of

natural resources and not for recyclable materials. Thus, they are sometimes too severe for improved waste materials to clear them. It might be an effective strategy for the standards to be assigned at several levels depending on the importance of the application.

In order to establish standards at several levels, based on the importance of the application, the concept of risk assessment will be necessary. We must positively include waste materials in our environment, and should not avoid or ignore them. To establish moral standards for environmental geotechnology and to reach a consensus of not only engineers, enterprisers, and politicians, but also other specialized or non-specialized peoples on promoting geotechnical waste utilization are strongly encouraged.

(3) To situate the geotechnical waste utilization to attain sustainable development.

The discussion should be focused on the issue of "which kind of waste should be used for which purpose or application?" in order to realize the concept of sustainable development properly, although it has been clarified that many kinds of waste can be reused for many geotechnical purposes. Their potential application is limited and cannot accept all types of waste materials, such as coal ash, molten slag, incinerated ash, surplus soil, and sludge. A strategic plan that includes distributing waste to the proper application is required. In addition, we must secure enough potential applications, both old and new. Necessarily, surplus soil and waste sludge discharged from geotechnical works should be reused in the field of the geotechnical engineering.

(4) To allow geotechnical engineers to contribute to geo-environmental problems much further.

Rather than geotechnical engineers, it is the environmental engineers, sanitary engineers, and geologists who have been the main contributors to counteracting geo-environmental problems, such as geo-environmental contamination and waste management. However geotechnical engineers should also contribute to solving these problems. This is because many of the people who face geo-environmental problems in practice are the geotechnical engineers. And, geotechnical engineers play an important role in coordinating and arranging projects in the construction industry. "Environmental geotechnology" has and will have an important role to fulfill in contributing to environmental preservation and promoting the concept of sustainable development.